



# Biochar: a win-win-win solution for sustainable small-scale farming in Sweden?

MALIN STENSSON 2018  
MVM12 MASTER'S THESIS 30 CREDITS  
ENVIRONMENTAL SCIENCE | LUND UNIVERSITY



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MVM12 master's thesis in environmental science 30 credits

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Lund 2018

Cover sheet image: golf clubs and organic vegetables from Håkan Rasmusson Golf och Lantbruk. Photography by Håkan Rasmusson. Reproduced with written permission.

The more you burn, the more you learn.  
*-Bob Wells, New England Biochar*



# Abstract

Biochar is a recalcitrant carbon rich solid product widely praised for the ability to improve soil fertility and sequester carbon, thereby improving crop yields and mitigating climate change. In addition to this, gaseous by products from production can be combusted for energy. Despite the recent global peaks in biochar research, studies focused on temperate regions are relatively scarce and few European farmers are familiar with the concept. At Håkan Rasmusson Golf och Lantbruk (HRGL), a 40-ha farm in southern Sweden, the potential for biochar production using cheap and simple production technology (a double barrel charcoal kiln) is being investigated. This report aims to theoretically study whether biochar production will benefit the farm in terms of increased crop yields, climate change mitigation and energy production, using a literature review and an enthalpy-based energy model. The results show that it is possible to fulfil the annual heat requirement of 30 000 kWh using a double barrel kiln. This could also result in a net offset of approximately 1.96 tons CO<sub>2</sub>e per year. Increased crop yields are unlikely, though biochar might positively affect other soil parameters, for example water holding capacity, in a way that could protect the soil from future resource limitations. However, there is a contradiction between production optimised for soil improvement and production optimised for climate regulation and energy production. In conclusion, biochar production is likely to be overall beneficial to HRGL. This report highlights the many factors to consider for a successful biochar production system but contains many assumptions and potential sources of error. It is strongly suggested that practical implementation is combined with monitoring to confirm the results of this study.



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## Abbreviations and symbols

CEC	Cation exchange capacity
CO <sub>2</sub> e	Carbon dioxide equivalents
GHG	Greenhouse gas
GWP	Global warming potential
HB500	Herbaceous biomass, 500°C
HB700	Herbaceous biomass, 700°C
HRGL	Håkan Rasmusson Golf och Lantbruk
MC	Moisture content
MRT	Mean residence time
NMVOC	Non-methane volatile organic compounds
OM	Organic matter
PAH	Polyaromatic hydrocarbons
PIC	Particulate inorganic matter
PyOC	Pyrogenic organic carbon
SBD	Soil bulk density
SOC	Soil organic carbon
SOM	Soil organic matter
SSA	Specific surface area
VM	Volatile matter
WB500	Woody biomass, 500°C
WB700	Woody biomass, 700°C
WHC	Water holding capacity

$c_p$	Specific heat capacity
$H_C$	Heat of combustion
$H_P$	Enthalpy of pyrolysis
$H_V$	Vaporisation enthalpy
$m$	Mass
$Q$	Energy
$T$	Temperature

# 1. Introduction

Accelerated global warming has led to atmospheric carbon dioxide (CO<sub>2</sub>) levels rising to over 400 ppm, resulting in widespread consequences to human health and natural systems (IPCC, 2014). While the atmospheric carbon (C) pool increases, the soil organic carbon (SOC) pool is steadily decreasing, partly due to intensive agricultural practices (Crews & Rumsey, 2017). This means that soils are becoming C depleted, leading to degraded soils with decreased fertility, degraded physical and biological properties and impaired water holding capacity (WHC) and soil microbial activity. Agriculture is also a major source of atmospheric greenhouse gas (GHG) emissions (ibid.). With an expected global population increase to 9.8 billion people by 2050 (UN, 2017), maintaining good soil quality and mitigating climate change are essential issues in ensuring food security for and health of the human population.

As one of many suggested solutions for climate change mitigation and sustainable agriculture, biochar has been receiving increasing attention. Biochar, illustrated by Figure 1, is a stable, recalcitrant C rich compound produced from organic material during pyrolysis. Pyrolysis is the conversion of lignocellulosic biomass into biochar and gaseous by-products under limited supply of oxygen (O<sub>2</sub>) (Roy & Dias, 2017). The by-products, syngas and bio-oil, can be combusted as a source of renewable energy (IBI, 2018). The difference between biochar and charcoal is mainly the intended use. Charcoal is used primarily as fuel while biochar is mixed into the soil as soil amendment and for atmospheric C capture and storage, as it possesses physicochemical properties suitable for long-term storage of C and soil improvement (Lehmann & Stephen, 2009).



**Figure 1: Biochar**

*Hands holding biochar (de Schwanberg, 2018). Reproduced with permission from Lund University.*

Recent peaks in biochar research have been greatly inspired by the discovery of patches of C rich, fertile soils in the Amazon Basin: Terra Preta de Indios (Montanarella & Lugato, 2013). Terra Preta (dark earth) are patches of charcoal rich soils created by the indigenous people of the Amazon up to 2000 years ago (Tenenbaum, 2009). Burning waste materials covered with soil caused thermochemical conversion of biomass into charcoal, making the soil darker and more fertile. Even today, these dark soils stand in stark contrast to the surrounding soils, which are paler and more nutrient poor due to low organic matter (OM) content, making them unsuitable for agriculture. It has been suggested that these rich soils were the key to the long-term survival of these indigenous communities, as it enabled continuous cultivation of the same, originally nutrient poor, Amazonian fields. Biochar is thereby by no means a revolutionary agricultural technique and is still used by millions all over the world (ibid.). It has however, as many other traditional farming practices, been forgotten during the evolution of modern agriculture. Following the discovery of Terra Preta, biochar has been re-discovered and rebranded as a tool for sustainable agriculture,

climate change mitigation, organic waste management and as a renewable energy source (Montanarella & Lugato, 2013).

Research indicates that biochar possesses great agricultural and environmental benefits, with its many advantages creating a cocktail of win-win-win solutions. However, despite positive research results, biochar is not yet widely implemented in European agriculture and very few Scandinavian farmers have knowledge of the concept (Otte & Vik, 2017; Bjerregaard, 2011). There is also a general lack of research on effects of biochar in temperate regions, as most studies have been conducted in the tropics. The results of biochar addition to temperate soils might differ from those in tropical soils. First, because of climatic differences like the fact that soils may freeze in winter while still reaching high temperatures in summer (Aller, 2016). Second, because the soils are physically and chemically different with temperate soils being generally less weathered and more alkaline (Jeffrey et al, 2017). Properties of biochar are greatly determined by external factors, primarily the organic biomass from which it is derived (hereafter feedstock) and pyrolysis production temperature (Downie et al, 2009).

## 1.1 The case study

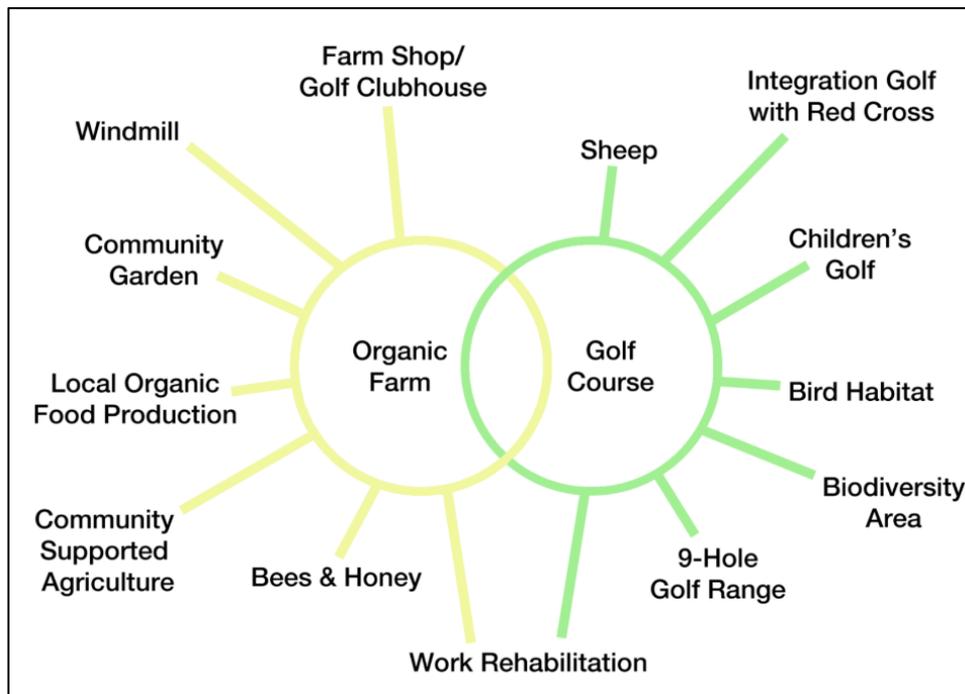
Håkan Rasmusson Golf och Lantbruk (HRGL) (Figure 2) is a 40-ha farm in Värpinge in southern Sweden. Since 1992, the farm has been converted from conventional farming with large monocultures into a golf course combined with organic farming (Håkan Rasmusson, pers. comm. 2018-02-15).



**Figure 2.** Håkan Rasmusson Golf och Lantbruk

*Håkan Rasmusson Golf och Lantbruk in Värpinge, Sweden. Source: Håkan Rasmusson. Reproduced with written permission from Håkan Rasmusson.*

Today, the organisation is multifunctional enterprise integrating multiple values, as illustrated by Figure 3. The aim is to develop an agricultural practice and land management that is sustainable in the long term and that creates shared values for the environment, the society and the business, thereby demonstrating the value of this relatively small piece of land.



**Figure 3.** Values of Håkan Rasmusson Golf och Lantbruk  
 Integrated values for the society, the environment and the business at Håkan Rasmusson Golf och Lantbruk. Source: Håkan Rasmusson. Reproduced with written permission from Håkan Rasmusson.

As part of the vision for a resilient agricultural practice with long term sustainability, the possibility of incorporating biochar production into the practice is being investigated. HRGL has received 50 000 SEK from Region Skånes Miljövärdssfond to be used for the development of an integrated farm-scale biochar production system. Biochar would be produced primarily from organic material grown on the golf course roughs using a modified double barrel kiln made from recycled diesel tanks (*Appendix 1: 2.1 Double barrel kiln*) in which pyrolytic gases would be combusted for heat production to make the farm more self-sufficient and limit the dependency on fossil fuels. In addition to this, the biochar that is produced can be mixed into the earth as a soil amendment and for climate regulation by creating an active C sink (*ibid.*).

## 1.2 Aim and objectives

The aim of this report is to theoretically investigate the potential for biochar production at HRGL. If this theoretical study leads to implementation of a successful biochar production system on the farm, it could serve as an incentive for future development of biochar research and production in temperate regions. To the best of my knowledge, this is the first case study investigating implementation of biochar with multiple perspectives on a small farm in northern Europe.

This report focuses on the use of pyrolysis products (biochar, syngas and bio-oil) in three aspects: soil improvement, climate regulation and energy production. A comparison is made between two general types of feedstock: woody and herbaceous biomass (distinguished primarily by their lignin and cellulose content), both of which could be cultivated on the golf course roughs. Crop yield is the variable chosen to represent effects on soil improvement, since this is what will provide direct benefit for the farmer. A modified double barrel kiln, which requires little economic investment and is simple to use, is the chosen production method. The double barrel kiln burns at around 500°C (O'Toole et al, 2013). For the sake of discussion, calculations based on a production temperature of 700°C are also included. Economic and legal aspects are not included, nor are potentially toxic effects of biochar, for example through formation of polyaromatic hydrocarbons (PAHs). The specific aim of the study is to answer the following:

1. To what extent can by-products from pyrolysis (syngas and bio-oil) contribute to energy production on the farm?
2. What effects can be expected in terms of crop yields following biochar soil amendment to the farm?
3. Can biochar production serve as a climate mitigation strategy for the farm by resulting in a net CO<sub>2</sub> offset?

Some general knowledge about biochar is required to follow the result of this study. For more information on pyrolysis, production technology, uses of biochar and biochar properties, please see Appendix 1.

## 2. Method

Three aspects of biochar production were investigated: energy production, soil amendment and climate regulation. Four production scenarios were included for the sake of discussion and comparison: herbaceous biomass at 500°C (HB500), herbaceous biomass at 700°C (HB700), woody biomass at 500°C (WB500) and woody biomass at 700°C (WB700). Woody biomass has a generally higher lignin and lower cellulose content relative to herbaceous biomass (Jahirul et al, 2012). Examples of woody species to be grown on the roughs are willow *Salix*, alder *Alnus* or birch *Betula*, while examples of herbaceous species are silver grass *Miscanthus* or reed canary grass *Phalaris arundinacea*.

### 2.1 Energy production

Energy production potential was calculated using an enthalpy-based energy model, illustrated by Figure 4. Biomass will be pyrolyzed in a large double barrel kiln (Appendix 1: 2. *Suitable production technology*) made from recycled diesel tanks. This is a variation of a low-tech retort kiln in which the syngas and bio-oil are directly combusted. Pyrolysis is an endothermic process (ibid.) and will consume some of the energy from combustion of the pyrolytic gas. Any energy not consumed by pyrolysis is excess heat and could potentially be recovered and used to heat the farm (Harsono et al, 2013). For calculations of the amount of excess energy potentially available for heat production, Microsoft Excel and a simple enthalpy-bases pyrolysis model was used, based on that used by Gronnow et al (2013). Energy-consuming processes of biochar production are the pyrolysis reaction, heating of feedstock and its water content and water vaporization. Energy-

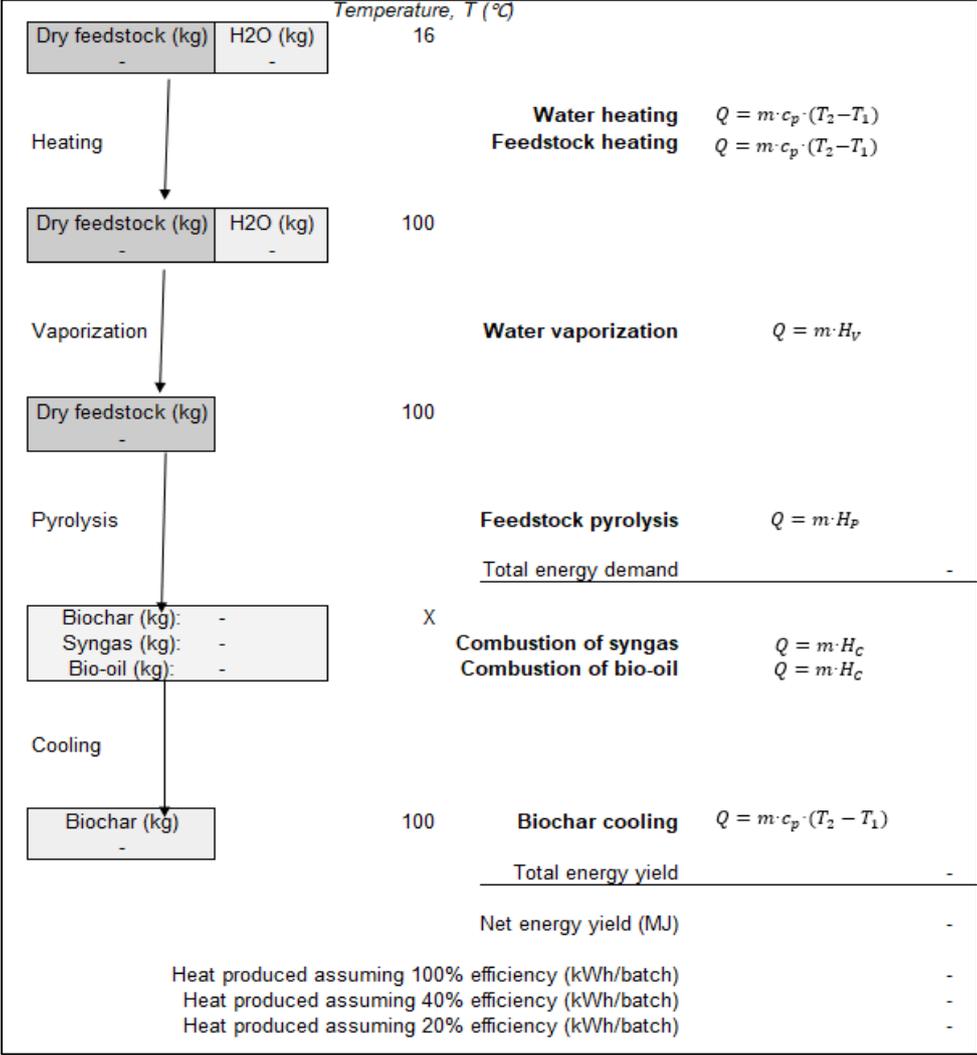
generating processes are combustion of produced pyrolytic gases and cooling of the resulting biochar.

Enthalpy is a measure of heat flow at constant pressure. Enthalpy of pyrolysis can be defined in several ways. For this purpose, the chosen definition is: the energy required to raise feedstock to the reaction temperature (sensible enthalpy) and to convert the solid feedstock into the reaction products (reaction enthalpy). This is the definition used by Daugaard & Brown (2003), and it is the total energy consumed by the feedstock during pyrolysis. The detailed process of biomass pyrolysis is very complex; in fact, the exact reaction scheme is not fully understood (Lohri et al, 2016; Jahirul et al, 2012). In this model, detailed reaction kinetics are not considered and a single value for enthalpy of pyrolysis is used. Some additional assumptions were made:

- Pyrolysis is an isothermal, endothermic reaction.
- The process is terminated before char gasification commences.
- Feedstock is pre-dried to 15% moisture content (MC).
- The following factors are disregarded:
  - Temperature dependency of reaction enthalpy of pyrolysis and specific heat capacity.
  - Interactions between feedstock and water that may affect enthalpy of vaporization.
  - Catalytic effects based on feedstock ash content (Appendix 1: 3.1.1 *Feedstock composition*).

Model input values are: 1) enthalpy of pyrolysis for various types of feedstock ( $H_P$ ), 2) vaporization enthalpy ( $H_V$ ) for water, specific heat capacity ( $c_p$ ) for water, feedstock and biochar, 3) heat of combustion ( $H_C$ ) of pyrolytic products, and 4) relative yields of biochar, syngas and bio-oil. 16°C is used as a base temperature as this is the average summer temperature in Scania (SMHI, 2016). Appropriate values were retrieved from previous publications using a literature search in Web of Science Core Collection. Search strings used were *pyrolysis AND enthalpy OR heat of reaction* as well as *biochar AND double barrel OR flame curtain OR Kon-Tiki OR enthalpy* and *biochar OR syngas OR bio-oil AND calorific value OR higher heating value* in the “topic” field. Studies were selected first by title, then by

abstract. Selection criteria included pyrolysis at similar temperatures (400-750°C) and similar feedstock (any woody or herbaceous biomass. When lacking values for herbaceous biomass, these was substituted for by values for agricultural residue such as corn stover, which has similar contents of lignin and cellulose relative to woody biomass (Jahirul et al, 2012)). In total, 95 studies were found of which 15 were relevant.



**Figure 4.** Energy production model

Enthalpy-based model used to calculate the excess energy (net energy yield) from pyrolysis of feedstocks in a low-tech kiln at different temperatures. Input values are specific heating capacity ( $c_p$ ), mass ( $m$ ), temperature ( $T$ ), vaporization enthalpy ( $H_v$ ), enthalpy of pyrolysis ( $H_p$ ) and heat of combustion of pyrolytic products ( $H_c$ ).

## 2.2 Soil amendment and climate regulation

A literature search was conducted using Web of Science Core Collection and the following search strings in the “topic” field: *biochar AND temperate AND crop yield OR crop productivity OR stability OR greenhouse gas OR CH<sub>4</sub> OR methane OR N<sub>2</sub>O OR nitrous oxide OR CO<sub>2</sub> OR carbon dioxide OR soil respiration*. No additional filter was used. The following search strings were also used and filtered to include studies from temperate regions only: *biochar AND stability OR leaching OR crop yield*. To further ensure a comprehensive list of studies, some additional papers were identified using the snowball method, i.e. selected based on citations in the other articles. The search resulted in 315 studies for climate regulation and 89 for soil amendment.

In screening of the articles, studies from non-temperate regions were excluded. Due to the relatively small number of studies from temperate regions no other geographical exclusions were made and no cut-off date was used. For the same reason, no limitation was made regarding soil type. Both meta-analysis, reviews and primary research papers were found. Meta-analyses were considered particularly valuable. Reviews, though an excellent source for background knowledge, were not used for the aim of this review as they only summarized previous findings but did not report any new data. Meta-analyses and primary research papers were screened first by title and then by abstract. Aside from limiting selection to temperate regions, only studies using pyrolysis derived biochar were used, and at similar temperatures (400-750°C). Feedstock types were limited to those that might be available on a small farm. For example, studies using sewage sludge as feedstock were excluded. Both field and laboratory studies were used, though primary research studies without controls were excluded. In total, the screening resulted in 46 relevant papers for climate regulation and 20 for soil amendment.

For a more complete assessment of the net climatic impact of biochar production a GHG balance, based on m factors identified by Woolf et al (2010), was calculated. When needed, a factor of 3,67 was used for conversion from C to CO<sub>2</sub>. Global warming potentials (GWP) used were 28 for methane (CH<sub>4</sub>) and 265 for nitrous oxide (N<sub>2</sub>O) (IPCC, 2014).

## 3. Results

### 3.1 Energy production

#### 3.1.1 Pyrolysis product yields

Generally assumed yields for slow pyrolysis are 35% biochar, 35% syngas and 30% bio-oil (Brown, 2009). However, studies using low-tech retort kilns have observed lower biochar yields than 35%. O'Toole et al (2013) used a double barrel kiln to produce biochar at a temperature of around 550°C, resulting in an average biochar yield of 24%. Note that the inner barrel held only 870 g of straw and that a larger barrel might yield different results. Cornelissen et al (2016) used a Kon-Tiki kiln (Appendix 1: *2.1 Suitable production technology*) to produce biochar at a temperature of around 715°C and obtained on average 22% biochar yield on a dry weight basis. Pandit et al (2017) acquired a 19% yield with a Kon-Tiki kiln at 600°C. It is known that higher temperatures produce lower char yields (Appendix 1: *3.1.3 Temperature*). Based on this information, a biochar yield of 20% is assumed for pyrolysis at 700°C and 30% at 500°C. Equal yields of syngas and bio-oil are assumed, i.e. 40% or 35%. The capacity of the kiln is 350 kg feedstock (Rasmusson, H., pers. comm. 2018-03-19). The feedstock is assumed to be pre-dried to 15% MC.

#### 3.1.2 Energy content of pyrolysis products

Values for heat of combustion ( $H_C$ ) for pyrolysis products are displayed in Table 1.

**Table 1. Heat of combustion**

Heat of combustion ( $H_c$ ) for pyrolysis products produced at 500°C and 700°C.

<sup>a</sup>Demirbas, 2001

<sup>b</sup>Jahirul et al, 2012

<sup>c</sup>Calculated based on Miller-Robbie et al (2015) (Appendix 2)

	Woody biomass (MJ/kg)		Herbaceous biomass (MJ/kg)	
	500°C	700°C	500°C	700°C
<b>Biochar<sup>a</sup></b>	29	31	28	30
<b>Bio-oil<sup>b</sup></b>	18	18	16	16
<b>Syngas<sup>c</sup></b>	7	7	6	6

### 3.1.3 Enthalpies and specific heat capacities

Measured values for enthalpy of pyrolysis ( $H_P$ ) can vary greatly. Observed values range from 0.2 MJ/kg (Gronnow et al, 2013; Van de Velden, 2010) to 1.6 MJ/kg (Daugaard & Brown, 2003; Yang et al, 2013). Enthalpies and specific heat capacities ( $c_p$ ) used in this report are displayed in Table 2.

**Table 2. Model input values**

Values used for energy calculations. Note different units.

<sup>a</sup>Gronnow et al, 2013

<sup>b</sup>Van de Velden, 2010

<sup>c</sup>Based on findings by Daugaard & Brown, 2003 and specific heat capacities by Van de Velden (2010) (Appendix 2)

		Specific heat capacity, $c$ , (kJ/kg·K)	Enthalpy of vaporization, $H_V$ (kJ/kg)	Enthalpy of pyrolysis, $H_P$ (MJ/kg)	
				500°C	700°C
<b>Water</b>	<i>Liquid</i>	4.18 <sup>a</sup>	2260 <sup>a</sup>	-	-
	<i>Gas</i>	2.08 <sup>a</sup>	-	-	-
<b>Woody biomass</b>		1.2 <sup>b</sup>	-	1.46 <sup>c</sup>	1.74 <sup>c</sup>
<b>Herbaceous biomass</b>		0.9 <sup>b</sup>	-	1.07 <sup>c</sup>	1.28 <sup>c</sup>
<b>Biochar</b>		1.2 <sup>a</sup>	-	-	-

### 3.1.4 The case study

Figure 5 exemplifies enthalpy calculations for WB500. Results for all scenarios are summarized in Table 3.

		Temperature, $T$ ( $^{\circ}\text{C}$ )	
Dry feedstock (kg)	H <sub>2</sub> O (kg)	16	
298	52		
Heating			
			<b>Water heating</b> $Q = m \cdot c_p \cdot (T_2 - T_1)$ 18 MJ
			<b>Feedstock heating</b> $Q = m \cdot c_p \cdot (T_2 - T_1)$ 30 MJ
Dry feedstock (kg)	H <sub>2</sub> O (kg)	100	
298	52		
Vaporization			
			<b>Water vaporization</b> $Q = m \cdot H_V$ 118 MJ
Dry feedstock (kg)		100	
298			
Pyrolysis			
			<b>Feedstock pyrolysis</b> $Q = m \cdot H_P$ 435 MJ
			<b>Total energy demand</b> 601 MJ
Biochar (kg):	89	500	
Syngas (kg):	104		
Bio-oil (kg):	104		
Cooling			
			<b>Combustion of syngas</b> $Q = m \cdot H_C$ 730 MJ
			<b>Combustion of bio-oil</b> $Q = m \cdot H_C$ 1877 MJ
Biochar (kg)		100	
89			
			<b>Biochar cooling</b> $Q = m \cdot c_p \cdot (T_2 - T_1)$ 43 MJ
			<b>Total energy yield</b> 2650 MJ
			<b>Net energy yield (MJ)</b> 2050
			Heat produced assuming 100% efficiency (kWh/batch) 574
			Heat produced assuming 40% efficiency (kWh/batch) 230
			Heat produced assuming 20% efficiency (kWh/batch) 115

**Figure 5.** Enthalpy calculation example  
Net energy yield from one 350 kg batch woody biomass at 500°C (WB500).

**Table 3. Results: energy production from a double barrel kiln**

Theoretical heat production at Håkan Rasmusson Golf & Lantbruk per batch feedstock using a 350 kg capacity double barrel kiln.

	Assuming 40% efficiency		Assuming 20% efficiency	
	Woody biomass (kWh/batch)	Herbaceous biomass (kWh/batch)	Woody biomass (kWh/batch)	Herbaceous biomass (kWh/batch)
500°C	230	208	115	104
700°C	262	238	131	119

For heating, the farm has an annual energy consumption of 50 000 kWh between October and April (Rasmusson, H., pers. comm. 2018-03-19). 40- 50% of this is supplied by the onsite windmill and the rest is purchased. An additional annual production of 30 000 kWh could hence make the farm self-sufficient during this time. For WB500 capable of producing 230 kWh per batch at 40% heat recovery efficiency, this would require running 131 batches per season, or 261 batches assuming 20% efficiency.

The capacity of one batch is 350 kg feedstock at 15% MC. Assuming 40% efficiency, this requires 38 973 kg dry woody feedstock for 131 batches. Fresh wood has a MC of 50% (Liss, 2008), hence this equals 77 946 kg fresh woody biomass, or 595 kg per batch. Assuming 30% biochar yield from dry weight feedstock, this would produce almost 11 700 kg biochar per year (89 kg per batch).

A double barrel kiln also requires start-up fuel to fill the space between the two barrels. Smebye et al (2017) found the start-up fuel requirement for retort kilns to be 15% of the amount of feedstock, i.e. an additional 11 692 kg is required, or in total 684 kg fresh wood per batch. The average growth of *Betula*, *Salix* and *Alnus* in southern Sweden is 6250 kg dry weight/ha/yr (Rytter et al, 2008). Thus, the maximum production capacity of 8 ha is 50 000 kg dry weight wood per year, or 100 000 kg fresh weight at 50% MC. This means that cultivation of these species on the golf roughs is theoretically sufficient to supply the farm with enough wood (89 638 kg) to supply 30 000 kWh through excess heat from biomass pyrolysis.

## 3.2 Soil improvement

The literature search resulted in 20 studies, consisting of one meta-analysis, four controlled experiments (greenhouse pot trials and mesocosms) and 15 field studies, all conducted in temperate soils. The results of the literature review are shown by Table 4. For details on soil mechanisms regarding biochar application to soil, please see Appendix 1: *4.3 Soil amendment*.

**Table 4. Crop yield effects following biochar amendment**

*Observed effects on crop yields following biochar amendment in temperate regions. Percentages do not sum up as several studies observed both positive and negative or neutral effects. Some negative and/or positive effect means that the study did observe an increase or decrease (significant or trend) in crop yields under some circumstances, but not to an extent that affected the overall conclusion of the study.*

<b>Source</b>	<b>Observed effects on crop yields following biochar amendment</b>			
	<b>Overall neutral</b>	<b>Some negative</b>	<b>Some positive</b>	<b>Overall positive</b>
<i>Ahmed &amp; Schoenau 2015</i>	x		x	
<i>Backer et al, 2016</i>			x	
<i>Boersma et al, 2017</i>	x			
<i>Borchard et al, 2014</i>	x	x		
<i>Brantley et al, 2015</i>		x	x	
<i>Griffin et al, 2017</i>	x		x	
<i>Haider et al, 2017</i>	x	x		
<i>Hammond et al, 2013</i>		x		x
<i>Hansen et al, 2017</i>	x			
<i>Jay et al, 2015</i>	x			
<i>Jeffrey et al, 2017</i>	x			
<i>Karer et al, 2013</i>	x	x	x	
<i>Kerré et al, 2017</i>				x
<i>Kloss et al, 2014</i>		x	x	
<i>Laird et al, 2017</i>	x		x	
<i>Nelissen et al, 2015</i>	x			
<i>Olmo et al, 2016</i>				x
<i>Rajkovich et al, 2012</i>		x	x	
<i>Sun et al, 2014a</i>	x	x	x	
<i>Xiao et al, 2017</i>				x
<b>Total, n</b>	12	8	9	4
<b>Total, %</b>	60	40	45	20

### 3.2.1 Positive crop yield response

20% of the 20 studies observed an overall positive effect on crop yields after biochar amendment, and 45% observed positive effects under certain circumstances. Several studies also observed positive effects on other soil parameters, most commonly improved WHC (Borchard et al, 2014; Haider et al, 2017; Karer et al, 2013; Nelissen et al, 2015; Sun et al, 2014a;) and increased pH (Hansen et al, 2017; Jay et al, 2015; Sun et al, 2014a).

For example, Olmo et al (2016) observed reduced soil compaction as well as increased WHC, pH, electrical conductivity and nutrient availability in biochar rich soils compared to other patches. Crop yields were also up to 22% higher. Of all observed changes, increases in water and nutrient availability were determined to be most important for increased crop yield. These effects were attributed to high internal porosity and low bulk density of biochar. Increased nutrient availability could be due either to high nutrient levels in the biochar itself or to changes in soil nutrient availability because of higher pH (Olmo et al, 2016). Backer et al (2016) showed increased yields (14%) and nitrogen (N) uptake for corn but not for soybean or switchgrass, in a loamy sand soil but not in a sandy clay loam. An interesting observation in the clay soil however was an increase in SOC, more than could be attributed to the C from the biochar itself. Two explanations were proposed: increased aboveground biomass (parts of which are left behind after harvest) or increased root proliferation. The latter theory was explained by the fact that biochar is known to alter soil WHC and bulk density (Backer et al, 2016).

Griffin et al (2017) found increased crop yields (8%) in the second year only of a four-year study. This was explained by an increase in soil pH as well as soil extractable nutrients, i.e. higher bioavailable concentrations of nutrients. This effect faded in following years, possibly because nutrients added by this particular biochar (which was of high ash content) were removed through plant uptake, leaching or sorption to minerals and OM. There was no change in the inorganic soil N pool, indicating that the biochar did not alter the soil N cycle in any significant way. The fact that yield increases were delayed to the second year might be that some biochars requires time to interact with the surrounding soil environment. Over time,

biochars may become more hydrophilic and create more surface functional groups through surface oxidation (Griffin et al, 2017).

Kerré et al (2017) studied soils containing 150-year-old biochar as a remnant from kiln production. The results showed a 23% increase in maize yields, which was thought to be related mostly to soil physical effects, rather than nutritional effects. The greatest yield benefit compared to controls was observed during the driest year of the study, suggesting that benefits are greater in resource limited soils. These results are interesting, as it is currently the only available study of historical black charcoal in temperate climates (ibid.). Every other identified study is short term in a biochar time perspective. This indicates that aging might have positive effects on biochar in soils. It has been suggested that surface oxidation happens over time, resulting in more surface functional groups and thus higher cation exchange capacity (CEC) and increased nutrient retention in aged biochar (Ding et al, 2017; Griffin et al, 2017; Haider et al, 2017; Hammond et al, 2013; Nelissen et al, 2015).

The largest crop yield increase was observed by Rajkovich et al, 2012 (at most 43%). However, it must be pointed out that this study not only lasted just 46 days but was also a greenhouse pot trial, and results are therefore not necessarily applicable to field conditions. The same soil and biochar combination can produce different results in a greenhouse compared to a field study (Haider et al, 2017). Jeffrey et al (2011) showed that the mean increase in crop productivity for pot trials was approximately three times greater than that of field trials; 15% and 5% respectively. Due to variability of the data it was not possible to determine whether this was due to differences in study design or type of crop, but it still provides an indication that pot trial results cannot necessarily be extrapolated to field conditions.

Hammond et al (2013) investigated wood biochar amendment to seven UK fields. This resulted in 3 fields with positive yield effects, 3 with neutral effects and one with negative effects. One case showed particularly good results: 117% increase. This was attributed to several factors. First, in this case the biochar had been stored outside for some years and showed higher CEC and exchangeable nutrient content. Also, biochar was applied as a top soil layer, allowing for interactions with fertilizers that were later applied or

perhaps increased soil temperature which facilitated germination. It may also have reduced soil evaporation (Hammond et al, 2013).

### **3.2.2 Negative crop yield response**

None of the 20 studies observed an overall significant decrease in crop yield response, though 40% did observe decreases under some circumstances. For example, Haider et al (2017) observed an initial crop yield decrease during the first year after biochar amendment. This was attributed to the liming effect of biochar leading to lower micronutrient availability to plants, and to increased aeration which affected soil cation ratios, in this case resulting in manganese (Mn) deficiency. The meta-analysis by Jeffrey et al (2017) found a significant overall crop yield decrease (on average -3%) in biochar amended temperate soils at a median application rate of 30 t/ha. Possibly, biochar raises soil pH beyond what is optimal for soil fertility, causing N-limitations and nutrient imbalance due to microbial immobilization or sorption of nutrients (ibid.). Several other studies have come to the same conclusion (Borchard et al, 2014; Brantley et al, 2015; Hammond et al, 2013; Sun et al, 2014a). This might also be the reason that some studies observed an upper threshold application rate, after which crop yields decreased. Hammond et al (2013), for example, established a threshold application rate of 30 t/ha. The lack of correlation between application rate and crop yield response has been observed in several other studies (Biederman & Harpole, 2013; Jeffrey et al, 2011; Liu et al, 2016).

### **3.2.3 Neutral crop yield response**

The majority of studies (60%) observed an overall neutral crop yield response. Neutral crop yield effects might be explained by inherent good soil quality of these temperate soils, like chemical fertility and structural robustness (Boersma et al, 2017). Potential benefits of biochar amendment could be masked as the system is already unaffected by resource limitation (ibid.). Temperate soils are often, due to being fertile with moderate pH as well as irrigated and fertilized for optimum yields, already optimal for plant growth (Borchard et al, 2014; Jeffrey et al, 2017; Nelissen et al, 2015; Sun

et al, 2014a). In such soils there is little room for improvement. Therefore, crop yield benefits are more pronounced in resource limited agroecosystems, such as heavily leached and acidic tropical soils (Jay et al, 2015; Jeffrey et al, 2017; Laird et al, 2017; Sun et al, 2014a). Crop yields were sometimes enhanced by biochar in resource limited soils, for example in unusually dry conditions (Karré et al, 2017). This suggests that yields in temperate soils could be enhanced by biochar during dry periods, and possibly also when limited by other factors. For example, Deb et al (2016) observed yield increases in phosphorous (P)-deficient soils but not in others. Interestingly, Hammond et al (2013) observed decreased yields in a sandy soil with originally poor nutrient content and low WHC. This was thought to be because the farm in question had adapted to these soil conditions by using optimized application of water and nutrients, and that this system was disrupted by biochar addition.

Biochar effects on soil properties do not necessarily translate into corresponding crop yield effects. Haider et al (2017) found biochar amendment to significantly reduce  $\text{NO}_3^-$  leaching and improve soil MC but not crop yields. Improvements in soil MC was attributed to changes in soil bulk density (SBD) and WHC because of the porous structure and high adsorption capacity of biochar. Reduced  $\text{NO}_3^-$  leaching was explained by sorption to biochar. Reduced total N uptake by plants was observed, probably for the same reason. Nelissen et al (2015) observed increased SOC content, increased plant available potassium (K) concentrations, reduced SBD, increased porosity and improved soil aggregation, but this did not result in increased crop yields. Biochar did not induce short term N immobilization. Instead, the explanation given was that the soil fertility status was already optimal for plant growth.

Feedstock greatly affects biochar soil improvement potential. Rajkovich et al (2012) found that feedstock caused eight times more variation in growth than did pyrolysis temperature. Griffin et al (2017) claim that biochar with high ash content may have short term nutrient benefits. The ash content of biochar is largely dependent on its feedstock. For example, wood derived biochar has relatively low ash content and therefore limited capacity to contribute nutrients to the soil (Boersma et al, 2017). Biochar from nutrient rich feedstock (e.g. animal manure) is better at providing a direct source of

nutrients (Boersma et al, 2017). The same is stated by Jeffrey et al (2017), who divide feedstock types into two categories with respect to crop yield effects: manures and biosolids vs. wood and straw. These were respectively labelled “nutrient” and “structure” since the former has a larger potential for a fertilizing effect and the latter a stronger potential to improve soil structure. Improvements on soil structure might include improved water retention, decreased SBD and habitat provision for soil biota. In tropical soils, nutrient biochars generate far larger effects on crop yield than structure biochars. In temperate soils however, it was found that, on average, neither group showed positive effects on crop yield performance (ibid.).

Due to the high adsorption capacity of biochar, nutrient enrichment of biochar makes a crucial difference for crop yield response compared to pure biochar addition (Brantley et al, 2015; Haider et al, 2017; Karer et al, 2013). This means that biochar should be saturated with nutrients before soil application. Nutrient enrichment can be achieved either by fertilizer input together with biochar or by composting biochar before soil addition.

#### **3.2.4 The case study**

Judging by the overall result of this literature review, a neutral effect on crop yields is most likely for HRGL. The conclusion that there is generally no effect on crop yields in temperate regions is supported by the only included meta-analysis (Jeffrey et al, 2017). The soil at HRGL is a fine clayey moraine (Jordartskarta, 2018), with a humus content of 1-2% (Rasmusson, H., pers. comm. 2018-03-19). Soil compaction is generally not a problem as large machines and tillage are avoided and sustainable farming techniques are applied; the quality of the soil is good (Rasmusson, H., pers. comm. 2018-05-08). Therefore, it seems unlikely that biochar amendment will result in any considerable crop yield increase at HRGL. Exceptions might occur for example during unusually dry years, due positive effects on other soil parameters. Negative crop yield effects can be avoided by applying fertilizer along with biochar and by composting biochar before application, as well as by avoiding high accumulative application rates.

### 3.3 Climate regulation

Biochar can directly contribute to climate regulation by sequestration of C in soils and by potentially reducing soil GHG emissions. To assess the net climatic impact, however, other aspects of biochar production must also be considered, as well as the stability of biochar in soils, i.e. how much of biochar C is lost from the soil over time. Based on suggestions by Woolf et al (2010), 7 emission avoiding or generating mechanisms were identified relating to this biochar production system. These are given below and quantified in a GHG balance in chapter 3.3.5 *The case study*:

1. CO<sub>2</sub> offset from C sequestration
2. Effect on N<sub>2</sub>O soil emissions
3. Effect on CH<sub>4</sub> soil emissions
4. Effect on soil respiration, i.e. CO<sub>2</sub> soil emissions
5. Fossil fuel offsets from pyrolysis energy production
6. CO<sub>2</sub> emissions from transportation
7. GHG emissions from kiln production

#### 3.3.1 Carbon sequestration

Studies of biochar stability in temperate soils are relatively scarce. During short term incubation studies, different biochar decomposition rates have been reported, for example 0,2% in 98 days (O'Toole et al, 2013), <5% in 22 months (Hansen et al, 2016), 0,3% per year for 2 years (Bamminger et al, 2018) and <12% in 115 days (Bruun et al, 2011). Bamminger et al (2018) estimated the mean residence time (MRT) of biochar in an agroecosystem in Germany (with similar climatic conditions as those in southern Sweden) to 369 years, assuming constant biochar-C mineralization. This was stated to coincide relatively well with other studies on biochar stability (ibid.). A 19 month in situ field incubation was conducted by Gronwald et al (2016) in northern Germany. Biochar pyrolyzed at 750°C showed no significant mineralization after 19 months, confirming high recalcitrance. Decomposition dynamics among different soil types showed no difference.

The average MRT was 60 years and the average half-life between 24 and 63 years, with large variation between replicates.

Biochar decomposition rates are often largest during initial incubation, and then decrease with time (Bruun et al, 2011; O'Toole et al, 2013). Therefore, MRT for biochar based on short term studies might be underestimated. Lutfalla et al (2017) evaluated pyrogenic organic carbon (PyOC) persistence under field conditions in five European long-term bare fallows (i.e. vegetation free field experiments) for 27-79 years. PyOC is a fraction of SOC that exists naturally in soils as a result of wildfires and is somewhat comparable to biochar. PyOC decreased more rapidly than expected, with an MRT of just 1.6 times that of SOC in general. The conclusion was that PyOC does have potential for long term C storage, but that its persistence may have been overestimated. PyOC loss occurred more slowly than SOC loss at all sites but was not inert. Overall, the MRT for PyOC obtained in this study (on average 116 years) were three to ten times shorter than commonly reported MRTs for PyOC (Lutfalla et al, 2017).

Biochar mineralization varies with feedstock, pyrolysis temperature, climate and soil conditions. In summary, biochar from higher lignin content feedstock produced at higher temperature and added to soils with high clay content in colder climates are more protected from mineralization (Wang et al, 2016b). For details on soil mechanisms regarding biochar mineralization, please see Appendix 1: *4.1 Carbon sequestration*.

### **3.3.2 N<sub>2</sub>O emissions**

20 articles on N<sub>2</sub>O emissions from temperate soils were identified, of which 5 were field experiments, and the rest used mesocosms or laboratory incubations. The longest study duration was 2 years. The result of the literature search is displayed in table 5. For details on the effect on soil N<sub>2</sub>O emissions, please see *Appendix: 4.2 Soil greenhouse gas emissions*.

**Table 5.** Effects on N<sub>2</sub>O soil emissions following biochar amendment

Observed effects on soil N<sub>2</sub>O emissions following biochar amendment in temperate regions. Percentages do not sum up as several studies observed both positive and negative or neutral effects. Some increase and/or decrease means that the study did observe increased or decreased emissions (significant or trend) under some circumstances, but not to an extent that affected the overall conclusion of the study.

Source	Observed effects on soil N <sub>2</sub> O emissions following biochar amendment			
	Overall neutral	Some increase	Some decrease	Overall decrease
Ameloot et al, 2013			x	
Bamminger et al, 2014			x	
Felber et al, 2014				x
Hangs et al, 2016				x
Harter et al, 2013				x
Horak et al, 2017				x
Kammann et al, 2011	x			
Krause et al, 2018	x		x	
Malghani et al, 2013			x	
Martin et al, 2015			x	
Nelissen et al, 2014			x	
Roman et al, 2016				x
Ramlow & Cotrufo, 2018			x	
Saarnio et al, 2013		x		
Schimmelpfennig et al, 2014			x	
Stewart et al, 2013				x
Sun et al, 2014b				x
Sun et al, 2017	x		x	
Verhoeven & Six, 2014		x		
Zheng et al, 2012				x
<b>Total, n</b>	3	2	9	8
<b>Total, %</b>	15	10	45	40

The majority of studies observed some or an overall decrease in soil N<sub>2</sub>O emissions (45% and 40% respectively). Observed N<sub>2</sub>O emission decreases ranged from 3% (Zheng et al, 2012) to 92% (Stewart et al, 2013). Schimmelpfennig et al (2014) state that a reduction rate of 50% is generally comparable with previous studies. However, note that field data generally show less pronounced effects on N<sub>2</sub>O emissions (Felber et al, 2014; Harter et al, 2013; Krause et al, 2018). For example, Felber et al (2014) found emission reductions in laboratory studies to be twice as large as those in the field. This was explained by better and more homogenous mixing of biochar and soil in the laboratory trial.

Two studies observed increased N<sub>2</sub>O emissions. Saarnio et al (2013) found that biochar increased soil respiration and N<sub>2</sub>O emissions in bare soil mesocosms under wet conditions. This was put down to increased soil WHC, which on the one hand was beneficial to crop yield but on the other created favourable conditions for denitrification. In dry vegetated soils, biochar decreased N<sub>2</sub>O flux. Verhoeven & Six (2014) also observed increased emissions following biochar amendment, which they stated to be in stark contrast to most previous findings. The study was also conducted in a Mediterranean climate, which makes extrapolation of these results to southern Sweden questionable. The given explanation for the increase was that biochar stimulated mineralization, nitrification and denitrification rates, directly or indirectly enhancing N<sub>2</sub>O emissions.

N<sub>2</sub>O soil emissions generally peak in relation to fertilization and precipitation events (Felber et al, 2014; Harter et al, 2013; Krause et al, 2018; Nelissen et al, 2014). Several studies have found emission decrease to be particularly pronounced in fertilized soils (Sun et al, 2014b; Zheng et al, 2012; Harter et al, 2013). Pyrolysis temperature also affects N<sub>2</sub>O emissions, and low temperature biochars tend to increase emissions. This is because denitrification suppressing mechanisms might be counteracted by provision of easily available substrate in the form of volatile organics (Ameloot et al, 2013; Kammann et al, 2011; Malghani et al, 2013; Nelissen et al, 2014; Schimmelpfennig et al, 2014). Few studies explored effects of biochar feedstock on emissions, though Ramlow & Cotrufo (2018) found that woody biochars have the greatest potential for reducing N<sub>2</sub>O emissions from fertilized soils.

### 3.3.3 CH<sub>4</sub> emissions

Available studies measuring CH<sub>4</sub> emissions from temperate soils following biochar amendment are scarce, and only 6 were found, displayed in Table 6. These were all incubation studies lasting between 60 days and 2 years. For details on the effect of biochar on soil CH<sub>4</sub> emissions, please see Appendix 1: 4.2 Soil greenhouse gas emissions.

**Table 6. Effects on CH<sub>4</sub> soil emissions following biochar amendment**

*Observed effects on soil CH<sub>4</sub> emissions following biochar amendment in temperate regions. Percentages do not sum up as several studies observed both positive and negative or neutral effects.*

Source	Observed effects on soil CH <sub>4</sub> emissions following biochar amendment		
	Overall neutral	Overall increase	Overall decrease
<i>Hangs et al, 2016</i>			x
<i>Malghani et al, 2013</i>	x		
<i>Ramlow &amp; Cortufo, 2018</i>			x
<i>Schimmelpfennig et al, 2014</i>			x
<i>Stewart et al, 2013</i>	x		
<i>Zheng et al, 2012</i>		x	
<b>Total, n</b>	2	1	3
<b>Total, %</b>	33	17	50

Factors affecting methanotrophic activity were found to be positively affected by biochar amendment by Hangs et al (2016). CH<sub>4</sub> oxidation rates observed by Schimmelpfennig et al (2014) were twice that of controls. Suggested mechanisms were increased aeration, leading to better conditions for methanotrophs, and N sorption immobilization by biochar which could inhibit other microorganisms (ibid.). However, decreases in CH<sub>4</sub> emissions are generally considered very small (<0,04%) of the annualized GHG benefit of biochar C sequestration (Ramlow & Cotrufo, 2018).

Zheng et al (2012) found increases in CH<sub>4</sub> emissions following biochar amendment of 5-72%. The study provides no suggested explanation for this observation. Ramlow & Cotrufo (2018) suggest that mechanisms for increased methanogenesis may include inputs of labile C from biochar under anaerobic conditions which stimulates CH<sub>4</sub> production, and reduced CH<sub>4</sub> oxidation due to changes in microbial community composition (ibid.).

### 3.3.4 CO<sub>2</sub> emission

8 articles, displayed in Table 7, measuring soil respiration following biochar amendment were found, of which 4 field studies and the rest incubation or greenhouse trials. Trial durations were between 37 days and 2 years. Results range from 43% reduction (Bamminger et al, 2014) to 21% increase compared to controls (Zheng et al, 2012). The majority of studies (39%) observed an overall neutral effect. For details on how biochar might affect soil respiration, see Appendix 1: 4.2 Soil greenhouse gas emissions.

**Table 7.** Effects on soil respiration following biochar amendment

*Observed effects on soil CO<sub>2</sub> emissions following biochar amendment in temperate regions. Percentages do not sum up as several studies observed both positive and negative or neutral effects. Some increase and/or decrease means that the study did observe increased or decreased emissions (significant or trend) under some circumstances, but not to an extent that affected the overall conclusion of the study.*

Source	Observed effects on soil CO <sub>2</sub> emissions following biochar amendment				
	Overall neutral	Some decrease	Some increase	Overall increase	Overall decrease
<i>Ameloot et al, 2013</i>			x		
<i>Bamminger et al, 2014</i>					x
<i>Chathurika et al, 2016</i>	x				
<i>Felber et al, 2014</i>				x	
<i>Gomez et al, 2014</i>		x	x		
<i>Haider et al, 2017</i>	x				
<i>Hangs et al, 2016</i>	x				
<i>He et al, 2016</i>	x				
<i>Jenkins et al, 2017</i>	x				
<i>Lanza et al, 2016</i>	x				
<i>Malghani et al, 2013</i>					x
<i>Martin et al, 2015</i>				x	
<i>Ramlow &amp; Cotrufo, 2018</i>	x				
<i>Saarnio et al, 2013</i>				x	
<i>Schimmelpfennig et al, 2014</i>					x
<i>Stewart et al, 2013</i>			x		
<i>Sun et al, 2014b</i>				x	
<i>Zheng et al, 2012</i>				x	
<b>Total, n</b>	7	1	3	5	3
<b>Total, %</b>	39	6	17	28	17

More recalcitrant biochar will likely cause lower CO<sub>2</sub> emissions than less recalcitrant biochar (Ameloot et al, 2013; Malghani et al, 2013; Stewart et al, 2013; Zheng et al, 2012). This agrees with Hangs et al (2016), who found that high temperature wood-based biochars with low volatile matter (VM) content tend to have the lowest effect on CO<sub>2</sub> emissions. Lower CO<sub>2</sub> emissions by more recalcitrant biochar could be explained by higher O:C ratio and fixed C content (Zheng et al, 2012). Negative priming and positive priming have both been observed by Stewart et al (2013). Positive priming was observed in soils with high soil C content. Overall, reports of priming effects have been very inconsistent, i.e. both positive or negative or neutral, and therefore the explanation might lie in more specific mechanisms (Hangs et al, 2016).

### 3.3.5. The case study

Based on this literature review, no obvious conclusion can be drawn about the effects on soil GHG emissions following biochar amendment at HRGL. The review indicates that decreased N<sub>2</sub>O emissions can probably be expected, as well as no effect or a possible increase in soil respiration. There is also an indication that higher pyrolysis temperature is more efficient for GHG emission reduction, as well as wood-derived biochar. However, there is not enough knowledge available to quantitatively predict effects on soil GHG emissions without site-specific trials. Therefore, effects on soil GHG emissions are considered negligible in the context of this case study and are not included in the GHG balance, summarized in Table 8.

**Table 8.** Greenhouse gas balance

Greenhouse gas balance for kiln pyrolysis of woody biomass feedstock at 500°C (WB500) and 700°C (WB700) based on emission avoiding and generating mechanisms by Woolf et al (2010). Negative values represent atmospheric CO<sub>2</sub> removal and positive values represented atmospheric CO<sub>2</sub> emissions. Values are based on a total energy production of 30 000 kWh.

Emission avoiding or generating mechanism	Comment	Emissions per year (kg CO <sub>2</sub> e)	
		WB500	WB700
CO <sub>2</sub> offset from C sequestration	Based on annual biochar production of 11 692 kg (WB500) and 6 843 kg (WB700).	-23 686	-16 952
Effect on N <sub>2</sub> O soil emissions	Assumed to be negligible	-	-
Effect on CH <sub>4</sub> soil emissions	Assumed to be negligible	-	-
Effect on CO <sub>2</sub> soil emissions	Assumed to be negligible	-	-
Fossil fuel offsets from pyrolysis energy production	Based on alternative emissions from district heating of 65 g CO <sub>2</sub> /kWh (Energiföretagen, 2017).	-1 950	-1 950
Emissions from transportation	Based on harvest of 8 ha every 3 years and emissions of 2.82 kg CO <sub>2</sub> /ℓ diesel (Miljöfordon, 2018).	+1 692	+1 692
GHG emissions from kiln production	Based on total mean emissions from woody biomass from retort kilns (Sparrevik et al, 2015).	+21 980	+12 865
<b>Total</b>		<b>-1 964</b>	<b>-4 345</b>
Net CO <sub>2</sub> offset (kg CO <sub>2</sub> e/kg biochar)		-0.17	-0.63

The balance is based on a maximum annual energy production of 30 000 kWh for scenario WB500 and WB700. HB500 and HB700 are not included as they were found to be less favourable in terms of energy production. Assumed biochar C contents is 75% at 700°C (Cornelissen et al, 2016) and 69% at 500°C (O'Toole et al, 2013). Assuming biochar yields of 30% at 500°C and 20% at 700°C, annual biochar production could be 11 692 kg (of which 8 067 kg C) and 6 843 kg (of which 5 132 kg C) respectively. The MRT or half-life of biochar cannot be accurately predicted based on this literature review, but total stability of biochar C cannot be assumed. It is known that the stability of biochar varies with type of feedstock and production temperature (Appendix 1: *4.1 Carbon sequestration*). Roberts et al (2010) propose, in an often cited and more advanced life cycle analysis of a biochar production system, a conservative estimate of 80% stabile C and 20% labile C, the latter of which is released to the atmosphere within the first few years of soil application. This was from biochar produced at 450°C and these values are therefore assumed for WB500. Higher temperature biochars are generally more stable. Therefore, a labile C content of 10% is assumed for WB700. In summary, the annual C sequestration potential is 6 453 kg C at 500°C and 4 619 kg C at 700°C.

Producing 30 000 kWh per year at HRGL means an annual offset of 30 000 kWh from district heating. CO<sub>2</sub> emissions from district heating are on average roughly 65 g CO<sub>2</sub>/kWh (Energiföretagen, 2017). This results in an additional annual offset of 1 950 kg CO<sub>2</sub>.

This on-site biochar production system requires no transportation of feedstock or biochar between locations. However, harvesting is an emission generating process that requires the use of diesel operated vehicles. For example: *Salix* (a perennial) is harvested approximately every three years (Jordbruksverket, 2010). Assuming a diesel consumption for harvest of 225 l/ha (Segerslätt, S., pers. comm. 2018-05-21), the fuel consumption is on average 600 l/year. Emissions from combustion of diesel is 2.82 k/CO<sub>2</sub>e (Miljöfordon, 2018), resulting in annual emissions of 1 692 CO<sub>2</sub>e.

The double barrel kiln will emit some non-CO<sub>2</sub> GHGs despite its clean burn design. No study of GHG emissions from double barrel kilns were found. However, Sparrevik et al (2015) measured emissions in other retort kilns at approximately 400°C. Since renewable biomass is used for

feedstock, CO<sub>2</sub> emissions are balanced by photosynthesis of continued cultivation. For woody feedstock, non-CO<sub>2</sub> emissions are roughly per kg biochar: 52 g CH<sub>4</sub> and 1.6 g NO<sub>x</sub> (ibid.). This includes emissions from initial combustion of start-up feedstock. The emissions correspond to 1.46 and 0.42 kg CO<sub>2</sub>e per kg biochar. Due to lack of data this value is assumed for both WB500 and WB700.

The result of this GHG balance is an annual offset of 1.96 tons CO<sub>2</sub>e for WB500, or 0.53 tons C. This corresponds to an offset of 0.17 kg CO<sub>2</sub>e per kg biochar produced. This means that the net climatic impact is positive, i.e. the net effect is removal of CO<sub>2</sub> from the atmosphere. For WB700, the offset is 0.63 kg CO<sub>2</sub>e per kg biochar produced.

## 4. Discussion

This study gives an overview of a biochar production system for a small Swedish farm. Exact values for energy production, yield improvements and C sequestration are difficult to estimate without site specific measurements, therefore the quantitative calculations are prone to error. The fact that almost all studies are based on short term studies lasting only a few years is also an issue, likewise the fact that many are laboratory trials. Despite these uncertainties, this review does give an idea of values and benefits from biochar production and highlights the many aspects to be considered when evaluating a biochar production system.

### 4.1 Energy production

WB700 is the most beneficial scenario for energy production. According to the model, pyrolysis of woody biomass at 500°C in a 350 kg double barrel kiln is capable of producing 30 000 kWh per year assuming 40% heat recovery efficiency, which would make HRGL energy self-sufficient during the winter months. This would require running 131 batches between October and April, meaning it would be relatively labour intensive despite the fact that the double barrel kiln does not require supervision while running (Holon, 2013). It would be possible to build two kilns that run simultaneously (Rasmusson, H., pers. comm. 2018-05-08), thus reducing the work load by half. Even so, this would mean running more than two batches every week throughout the winter season. This is assuming that 40% heat recovery efficiency. The low value assumed for heat recovery efficiency was chosen due to the fact that energy production is ordinarily not the intended use for a double barrel kiln, hence it is not optimized for heat recovery nor

built from insulating materials. If the kiln was built to improve heat recovery efficiency, both work load and required feedstock could be reduced.

The double barrel kiln is easy to construct and handle and has the advantage of being self-sustaining and not very labour intensive while operating (Holon, 2013). Because it is a batch kiln that does not need to run continuously, production can have adjusted to fill gaps from the weather dependent the windmill (Rasmusson, H., pers. comm 2018-03-19). It is however important to note that no study of biochar production in a double barrel of this size was found. Scaling up the size from a small model may affect the efficiency of the kiln.

A disadvantage of the double barrel kiln is the fact that it allows little control over production parameters (Appendix 1: *3.1 Factors affecting biochar yield and properties*). The kiln will also wear out with time and will need to be replaced. No comparable number was found for a double barrel, but a Kon-Tiki steel kiln capable of yielding 100 kg biochar per run has a life expectancy of 100 runs (Smebye et al, 2017). If the same is true for the double barrel kilns, they will need to be replaced at least every two years when used so frequently.

Measures can be taken to increase the energy yield from pyrolysis. For example, feedstock should not be packed too tightly so that gases can easily escape (Cornelissen et al, 2016). Minimising feedstock MC is also beneficial as this creates bio-oil with lower MC and higher energy content (Jahirul et al, 2012). Also, the higher the MC, the more combustion energy is needed to evaporate the water and heat the feedstock.

Literature tells us that temperature and feedstock have a large influence on biochar characteristics and pyrolysis product yields (Appendix 1: *3.1 Factors affecting biochar yield and properties*). In this case, the difference between feedstock types or temperatures is not that large. The small difference between feedstocks (22 kWh per batch (around 10%) at 40% efficiency) is likely due to the fact that woody and herbaceous biomass are both structure feedstocks (Jeffrey et al, 2017). If comparison was made between feedstocks with very different nutrient content and structure, for instance wood and manure, the result might be different due to different energy densities of the pyrolytic gases. The difference in energy production between temperatures is slightly higher than between feedstocks (32 kWh

per batch (around 13%) at 40% efficiency). This is in line with most existing literature on the topic, where temperature is often described as the main determinant for biochar production (Brownsort, 2009; Downie et al, 2009).

The calculations of energy production potential are a large source of uncertainty in this report. The enthalpy model contains many possible sources of error, primarily the assumptions mentioned in the method (chapter 2.1 *Energy production*). Input values are also collected from a range of papers using different combinations of feedstock, temperature and measurement techniques. Modification of the model, for example by incorporating temperature dependency of pyrolysis enthalpy, might change the results (Ullner, M. pers. comm. 2018-05-02). Therefore, a trial and error-based approach combined with monitoring is suggested during initial production in order to optimise the process. For example, measuring the heat of combustion with a calorimeter during an initial test run is suggested. Despite these uncertainties however, the results show that it is more than possible to produce enough feedstock on the golf course roughs to produce 30 000 kWh. Note that this is based on an adult tree stand. If needed, agricultural residue such as straw (comparable to herbaceous biomass (Jahirul et al, 2012)) could supplement to reach feedstock requirements.

## 4.2 Soil improvement

Based on this review there is no guaranteed effect, positive or negative, on crop yields following biochar amendment in temperate climates. It should be kept in mind that this is a general review containing studies with large variations in geographic location and study design, e.g. soil texture and pH, nutrient balance, weather conditions, biochar aging, application rate, incorporation depth, crop type and feedstock type. Biochar used in these studies was also mostly produced using more advanced methods than low-tech retort kilns. Of the 20 studies used in the literature review, 60% observed an overall neutral effect on crop yields, 3% observed an overall positive effect and 0% observed an overall negative effect. Without taking specific soil mechanisms into account, this does indicate that it is unlikely that biochar soil amendment will result in negative effects on crop yields and

thus be a disadvantage to the farmer. Positive effects are most likely to be obtained during growing seasons that are resource limited in some way, e.g. by drought (Deb et al, 2016; Hammond et al, 2013; Kerré et al, 2017).

Most studies included in this review did not focus on comparison between biochar from different temperatures, but literature states that low pyrolysis temperatures create biochar better suited for soil improvement, as this creates biochar with higher CEC (Appendix 1: 2.1.2 *Temperature*). Both woody and herbaceous biomass fall under the category of structure feedstock and therefore neither has great potential as fertilizing agents (Jeffrey et al, 2017). Wood has a particularly low ash content (Boersma et al, 2017). However, they both have potential to create biochar that improves soil structure, for example by improving WHC and creating habitats for soil biota (Jeffrey et al, 2017). Also, even 500°C is considered a relatively high pyrolysis temperature. Yue et al (2016) actually claim that 500°C is the peak temperature for maximum specific surface area (SSA) and porosity, which are good biochar characteristics for soil improvement (Appendix 1: 3.2 *Physical and structural properties*). Considering these facts, HB500 is the most beneficial scenario for soil amendment purposes.

It seems that effects on soil parameters do not necessarily translate into corresponding crop yield responses. This agrees with previous findings (Deb et al, 2016). Many studies observed positive effects on various soil factors, for example WHC and SBD (Haider et al, 2017; Nelissen et al, 2015) without obtaining increased crop yields. This indicates a large complexity of biochar-soil-plant interactions and likely feedback effects that interact to result in the final effect on crop yields and plant growth. It also indicates that, even in the absence of direct crop yield benefits, there may be other indirect benefits. For example, sorption on biochar means possible reduction in N leaching (Nanda et al, 2016; Li et al, 2016; Qambrani et al, 2017). Also, almost all biomass P is retained in biochar which may therefore serve as a way to recycle P (Appendix 1: 4.3.3 *Nutrient retention and bioavailability*). Though the N content of biochar is low, (Appendix 1: 4.3.3 *Nutrient retention and bioavailability*), this could be fairly easily compensated by choosing species such as *Alnus*, in symbiosis with N-fixing bacteria, for cultivation on the roughs. Therefore, it is possible that biochar is useful even in temperate regions to reduce agricultural production costs through e.g.

liming and reduced fertilizer needs. It also seems that resource limited soils benefit from biochar application (Deb et al, 2016; Hammond et al, 2013; Kerré et al, 2017). Perhaps biochar amended soils will have a future advantage in terms of climate change resilience? It is also indicated that aging has a positive effect on biochar for soil improvement (Ding et al, 2017; Griffin et al, 2017; Haider et al, 2017; Hammond et al, 2013; Nelissen et al, 2015), therefore potential benefits may become evident in the future.

There is indication of threshold biochar application rates in order to avoid higher than optimal pH, after which negative yield effects can occur (Biederman & Harpole, 2013; Jeffrey et al, 2011; Liu et al, 2016). At HRGL, it is possible to produce almost 12 000 kg biochar per year if the method is optimized for biochar production (based on 30% biochar yield of 39 973 kg dry weight wood). Spread over 40 ha, this equals addition of 300 kg biochar per hectare, i.e. well below observed threshold application rates of approximately 30 t/ha (Hammond et al, 2013). However, accumulative addition over several years to only a few selected fields, or in a greenhouse for instance, might risk exceeding this limit, which is something to be cautious of. This is also something to be aware of with aspect to climate regulation potential, as continuous addition of biochar to soil for C sequestration purposes might negatively affect soil ecology. It also means that continuously increasing biochar application rates in the hope of increasing crop yields in temperate regions will not work. However, this is unlikely to be an issue at HRGL due to the small quantity of biochar produced relative to the size of the estate.

### 4.3 Climate regulation

Based on this review, this biochar production system in its entirety is a climate positive process capable of capturing and storing up to 1.96 tons CO<sub>2e</sub> per year (WB500). For comparison, the annual consumption-based emissions of CO<sub>2e</sub> in Sweden is close to 11 tons per capita (Naturvårdsverket, 2017). If possible to increase the temperature of the double barrel kiln, the climatic benefit could be greater (4.35 tons CO<sub>2e</sub> per year for WB700), because of difference in pyrolysis products yield

distributions. This is based on the emission generating and avoiding mechanisms directly related to biochar production, not a full life cycle analysis. Even so, the net CO<sub>2</sub> offset is small. This is largely due to emissions from combustion of pyrolytic gas and start-up material, which may even be underestimated in this GHG balance. Incomplete combustion of pyrolytic gas is likely to cause some additional emissions in the form of CO, non-methane volatile organic compounds (NMVOC) and products of incomplete combustion (PIC) (Cornelissen et al, 2016; Sparrevik et al, 2015). Perhaps investment in more advanced production technology would provide an opportunity to further reduce atmospheric emissions and also utilize more heat, in favour of the GHG balance.

Biochar potential for C sequestration and soil GHG emission reduction are perhaps the most interesting aspect of the climate regulating potential of biochar. This report assumes no net change in soil GHG emissions. Many studies observed decreased N<sub>2</sub>O soil emissions (Felber et al, 2014; Hangs et al, 2016; Harter et al, 2013; Horak et al, 2017; Roman et al, 2016; Stewart et al, 2013; Sun et al, 2014b; Zheng et al, 2012), which would have a positive effect the GHG balance. Whether changes in soil respiration will have any considerable effect on the GHG balance is difficult to say. An understanding of the influence of feedstock and production conditions on the long-term stability of biochar (Appendix 1: *4.1 Carbon sequestration*) is pivotal for its function as a C mitigation measure. Unfortunately, neither biochar stability or soil emission reductions can be accurately predicted using this literature review. Therefore, soil application of biochar at HRGL should be combined with monitoring of soil GHG emissions and biochar decomposition. Studies included in this review have estimated biochar MRT to between 60 years (Gronwald et al, 2016) and 369 years (Bamminger et al, 2018). However, in many cases MRTs are based on a constant biochar mineralization rate observed during a relatively short-term study. Since there is evidence of decreased mineralization rates over time (Bruun et al, 2011; O'Toole et al, 2013), this might lead to an underestimation of biochar MRT. Due to the colder climate and hence generally slower microbial activity, it can at least be assumed that MRTs of biochar in temperate soil exceeds that of tropical soils (He et al, 2016). High soil clay content, high pyrolysis temperature and high feedstock lignin content are other favourable factors for longer biochar

stability (Wang et al, 2016b). The same is true for reduced N<sub>2</sub>O and CO<sub>2</sub> emissions (Hangs et al, 2016; Ramlow & Cotrufo, 2018; Schimmelpfennig et al, 2014). Hence, WB700 is the best scenario for C sequestration. This means that there is a trade-off between optimizing the biochar production system for C storage and energy production versus for enhancing soil fertility (i.e. CEC), which agrees with conclusions by several previous reviews (Archontoulis et al, 2016; Crombie et al, 2015; Aller, 2016).

## 4.4 Outlook

Low-tech retort kilns are the most technically and financially feasible option for small-scale farmers to produce biochar (Lohri et al, 2016; O'Toole et al, 2013; Rasmusson, H., pers. comm. 2018-02-15). However, due to the inefficient design of, for instance, the double barrel kiln, the net climatic impact is small and energy production is less efficient than for more advanced retort kilns. To facilitate implementation of biochar production systems for small-scale farmers (and promote the use of biochar as a sustainable farming method), future research should focus on developing production techniques that are both financially reasonable for smaller farms, efficient, non-polluting and capable of producing high quality biochar.



## 5. Conclusion

- There is a contradiction between optimising biochar for different purposes. Low temperature biochars from nutrient rich feedstock are favourable for soil improvement, while high temperature biochars from structural feedstock are better for C sequestration and energy production.
- Crop yield benefits are not likely for HRGL. Production can therefore be optimised for climate change mitigation and energy production, i.e. woody feedstock at high production temperatures.
- A double barrel kiln is a feasible method for energy production at HRGL but less so for climate regulation due to high emissions. It also has the disadvantage of little control over production parameters and a short life-span.
- The golf course roughs have the capacity to produce more than enough feedstock to make the farm self-sufficient in terms of heat production through pyrolysis.
- The combination of soil type and climatic conditions on the farm is probably well adjusted for long term biochar stability. There is also a possibility of reduced GHG soil emissions.
- Biochar could have positive effects on soil parameters other than crop yield, especially after a few years of aging. Thus, biochar might function as an insurance policy for the future and contribute to more resilient soils in the face of future challenges such as climate change and fertilizer shortage.
- The results of this study are overall positive but prone to error due to calculations based on literature values and a literature review with relatively few limitations. It is important that HRGL conducts measurements to follow up and corroborate or reject the results of this study.



## 6. Acknowledgement

First of all, I would like to say a huge and well deserved thank you to my supervisor Håkan Wallander. This report could not have been written without your comments, input and guidance. You not only contributed with insight based on your vast knowledge of soil biology but also helped me limit my work and streamline my thoughts.

Secondly, another huge thank you to Håkan Rasmusson for inspiration and hope regarding the future development of agriculture. Your efforts are vital and set an example to both farmers and consumers of what can be achieved by thinking outside the box.

Thank you to Erik Remvig at Håkan Rasmusson Golf och Lantbruk and Madeleine Brask at Miljöbron for your comments. Thank you also to Magnus Ullner at Lund University, Sten Segerslätt at REAB, Markus Pålsson at Lund municipality and Annika Hansson at Trelleborg municipality for taking the time to share your knowledge and provide guidance.

Last, but not in any way least, thank you to my wonderful husband Linus for your support and patience during every moment of frustration and every late night spent in front of the computer. I love you.



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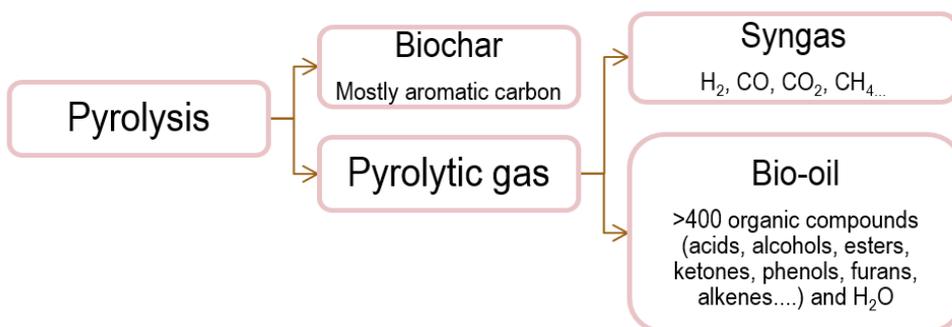
# Appendix 1: Theory

## 1. Pyrolysis

Pyrolysis is the most studied and well-established technique for biochar production (Amonette & Joseph, 2009; Li et al, 2016). Pyrolysis is the breaking down of a material (lysis) by heat (pyro) at temperatures between 300°C and 1000°C (Brownsort, 2009; Lehmann & Stephen, 2009). This causes volume reduction of biomass due to mass loss, mostly in the form of volatile organics and gases from the pyrolyzing solid (Gronnow et al, 2013). The C and mineral skeleton that remains will contain the rudimentary porosity and structure of the original material (Downie et al, 2009). Harder biomass will result in biochar with the same shape and structure, while biomass with higher MC will not (Gustafsson, 2013).

There are several types of pyrolysis, distinguished by e.g. heating rate, reaction time and product distribution (Nanda et al, 2016). The two main types of pyrolysis are fast pyrolysis and slow pyrolysis (Brownsort, 2009). Slow pyrolysis is characterised by slower heating rate (5-10°C/min), longer vapour residence time and a wider temperature range (Lian & Xing, 2017). Slow pyrolysis is most similar to a naturally occurring burning process (ibid). Biochar production using a low-tech retort kiln, as in this case study, will mirror slow pyrolysis conditions (Sparrevik et al, 2015).

Pyrolysis generates two products: solid residue (char) and pyrolytic gas. The pyrolytic gas can in turn be divided into non-condensable gases (syngas) and condensable liquids (bio-oil) (Brown, 2009), as shown by Figure 6. The relative energy and mass variation depends largely on pyrolysis conditions. Typical yields are 70% bio-oil, 15% biochar and 15% syngas for fast pyrolysis and 30% bio-oil, 35% biochar and 35% syngas for slow pyrolysis (Kung et al, 2013; Miller-Robbie et al, 2015).



**Figure 6.** Pyrolysis products

*Pyrolysis of biomass results in biochar, syngas and bio-oil.*

### 1.1 Biochar

Biochar is the black solid pyrolysis product. Compared to the original feedstock, biochar is more stable and C-rich with a higher energy content and altered physical properties (Gronnow et al, 2013). It is a heterogeneous material with large variations in structural properties, generated from thermochemical changes in the original feedstock structure during pyrolysis (Aller, 2016). Biochar can be used in a range of applications, such as for C sequestration and soil improvement as described in this report. A more detailed description of the physicochemical properties of biochar is given in chapter 2.3 *Biochar physicochemical properties*.

### 1.2 Syngas

Syngas (synthetic gas) is composed of non-condensable gases of low molecular weight, mainly CO<sub>2</sub>, carbon monoxide (CO), hydrogen gas (H<sub>2</sub>) and CH<sub>4</sub> (Chen et al, 2016; Kung et al, 2013; Tsai et al, 2015). Other non-condensable hydrocarbons are also present (Kung et al, 2013; Shen et al, 2017). The usual mixture of gases in percent volume is roughly 9-55% CO<sub>2</sub>, 16-51% CO, 2-43% H<sub>2</sub> and 4-11% CH<sub>4</sub> (Gustafsson, 2013). Most of the gases are flammable and provide energy values in proportion to their individual properties, except CO<sub>2</sub> which does not emit heat during combustion and thus will negatively affect the energy value of gas (Brownsort, 2009; Gustafsson, 2013).

Syngas is an energy carrier that, if collected, can be burned to produce heat or electricity (IBI, 2018). For bio-oil and syngas, the energy density is generally lower than for most fossil fuels, though higher than that of the raw feedstock from which it is derived, as energy is concentrated into a lower volume product (Chen et al, 2016; Tsai et al, 2015).

### **1.3 Bio-oil**

Bio-oil is a dark brown liquid, which, like syngas, can be combusted and used for fuel (Chen et al, 2016). Bio-oil has a higher calorific value than syngas (Miller-Robbie et al, 2015). The term oil is somewhat confusing, as this organic liquid product is generally hydrophilic (Brownsort, 2009). Bio-oil consists of high molecular weight condensable compounds divided into an aqueous phase (water, acids, aldehydes, ketones, alcohols, ethers and esters) and an organic phase (phenolics, carbonyls, tar and heavy oil) (Nanda et al, 2016). The composition and energy content differ widely depending on pyrolysis method and parameters (Yue et al, 2016). Bio-oil also contains non-condensable organic compounds, e.g. benzene, phenols, N-heterocyclic compounds, and PAHs (Shen et al, 2017). These can condense with small particle impurities to form more complex structures that damage more advanced pyrolysis equipment. Several of these compounds are also toxic and environmentally hazardous and their formation is regarded as a limiting factor for pyrolysis, even though there are many approaches for removal of such damaging substances in the production process (ibid.).

Aside from combustion for energy production, bio-oil can be converted into fuel or blended with ethanol or gasoline to be directly used as fuel (Roy & Dias, 2017). An alternate use for bio-oil is to refine and process it to produce higher quality fuels or chemical products such as resins and fertilizers (Brownsort, 2009; Kung et al, 2013). Despite this, it is sometimes disposed of as waste since it is a complex substance that tends to contain a wide variety of unwanted chemical compounds (Harsono et al, 2013).

## 2. Suitable production technology

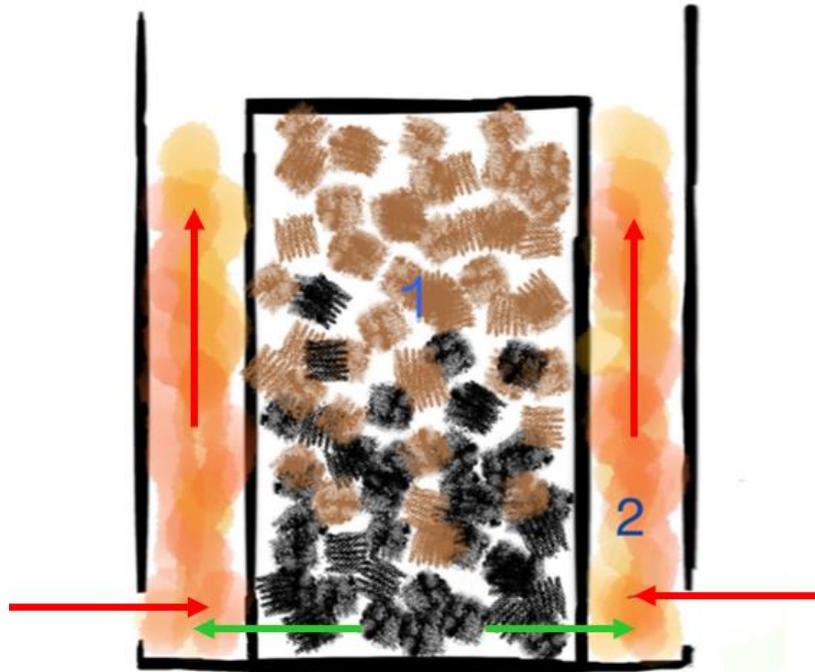
Charcoal production is one of the oldest production technologies in existence (Brown, 2009). The earliest kinds of charcoal kilns consist of pits or mounds where smouldering wood is buried under or above ground. Pit and mound kilns are still used in many parts of the world, but they are inefficient and polluting. Today, advanced kilns and modern bio-refineries that have the ability to mitigate atmospheric emissions and produce higher charcoal yields are available. Improved technology provides the opportunity to better control the properties of biochar for agronomic and C sequestration purposes (ibid.). For small-scale farmers however, simple kiln and batch technologies are the most feasible option regarding technical, financial, environmental and health aspects (Lohri et al, 2016; O'Toole et al, 2013).

In a retort kiln, the pyrolytic gases are redirected so that they must pass through a flame, where they are combusted, releasing enough energy to sustain the endothermic pyrolysis reaction (Cornelissen et al, 2016; Sparrevik et al, 2015). These kilns are also less polluting as they operate with a so called clean burn, reducing pollutant emissions such as CH<sub>4</sub> and resulting in a smokeless fire with no visible emissions (ibid.). Two examples of low-tech retort kilns are the double barrel kiln and the Kon-Tiki kiln (a.k.a. open flame curtain kiln). The double barrel kiln, briefly described below, is the chosen method for this case study.

### 2.1 Double barrel charcoal kiln

Figure 7 shows an illustration of a double barrel kiln. A smaller barrel is filled with feedstock and placed upside-down in a larger barrel, so that the feedstock is not directly exposed to air (Holon, 2013; O'Toole et al, 2013). The space between the barrels is then filled with starter material and lit. When the fire has reached high enough temperatures, the feedstock in the inner barrel will start pyrolyzing. After the starter material has been combusted, the fire will be sustained by pyrolytic gases seeping out the bottom of the inner barrel. Vents in the outer barrel keep the fire oxygenated and enables combustion of pyrolytic gases. This kiln does not need to be quenched; when all the feedstock has charred, the fire will go out (Holon,

2013). The double barrel kiln operates at around 500°C (O'Toole et al, 2013).



**Figure 7.** Double barrel pyrolysis kiln

*Flows of air (red arrows) and pyrolytic gas (green arrows) during pyrolysis in a double barrel kiln. The pyrolysis zone (1) and the combustion zone (2) are separated by the walls of the inner barrel.*

### 3. Biochar physicochemical properties

The defining properties of biochar is high C content and resistance to breakdown along with high porosity and high surface area (Brassard et al, 2016; Lehmann & Stephen, 2009; Mimmo et al, 2014; Qambrani et al, 2017). A large variation in other properties have been observed. Both physical and chemical properties of biochar contribute to its function as a tool for environmental management, and different biochars might provide different benefits for the same application (Biederman & Harpole, 2013; Nanda et al, 2016). The efficiency of biochar in most applications is significantly dependent on its C content, surface area, pore size distribution,

alkalinity, CEC and elemental composition (Nanda et al, 2016; Qambrani et al, 2017).

### **3.1 Factors affecting biochar yield and properties**

Defining factors determining yield distributions of pyrolysis products include feedstock composition and pre-treatment, temperature, heating rate, pressure, material flow rate, gaseous atmosphere and reaction residence time. Of these, pyrolysis temperature and feedstock composition are considered to be the most important (Downie et al, 2009; Mimmo et al, 2014; Qambrani et al, 2017; Tsai et al, 2015). Heating rates and pressure have second highest influence, because they affect physical mass transfer of volatiles evolving at the given temperatures from reacting particles (Downie et al, 2009). A low-tech retort kiln does not give the opportunity to control all these parameters, therefore only a selection is described below.

#### *3.1.1 Feedstock composition*

Any biomass can be used to produce biochar. It is typical to use plant residues from agriculture (e.g. straw, husk, corn cob), forestry (e.g. sawdust and insect infested wood) or grasslands (e.g. switchgrass and elephant grass) (Nanda et al, 2016). Biomass consists mainly of cellulose, hemicellulose and lignin, as well as smaller quantities of organic molecules (extractives) and inorganic minerals (ash) (Brown, 2009; Brownsort, 2009).

The relative composition of lignin, cellulose and hemi-cellulose in biomass affects biochar structural properties (Brown, 2009) Lignin-rich feedstock such as woody and herbaceous biomass usually produces a more C-rich biochar, while sewage sludge and manure will produce biochars with higher nutrient content (Bruun et al, 2011). Minerals, particularly alkali metals, have a catalytic effect on the pyrolysis process. Alkali metals increase the rate of biomass devolatilization during pyrolysis by increasing C exchange, which catalyses secondary cracking and increases char yield (Brownsort, 2009; Gustafsson, 2013; Li et al, 2016; Shen et al, 2017). Minerals and metals typically remain in the char after biomass oxidation and are then referred to as ash (Brown, 2009). Due to the low concentrations of

extractives in biomass, they do not influence charcoal yield, however they do influence gaseous emission profiles (ibid.).

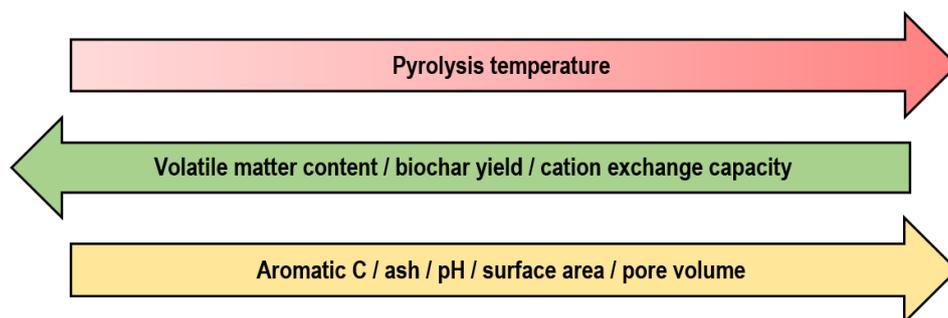
### *3.1.2 Feedstock pre-treatment*

To meet requirements for MC, particle size and purity, pre-treatment of feedstock may be necessary depending on the production technology (Gustafsson, 2013). This commonly entails sorting, grinding and drying. The purpose of sorting is to eliminate any unwanted larger objects from the feedstock, reduce feedstock particle size (on which heat transfer is largely dependent), and drying to increase pyrolysis efficiency (ibid.).

### *3.1.3 Temperature*

Temperature is the main controlling variable of pyrolysis reaction kinetics because the fundamental physical changes that occur during pyrolysis are all temperature dependent (Brownsort, 2009; Downie et al, 2009).

Higher temperatures lead to lower char yields and higher gas yields. This is attributed to decomposition of more organic materials at higher temperature, as more VM is forced out of the char (Mimmo et al, 2014; Yuan et al, 2015; Yue et al, 2016). Due to lower VM content, higher temperature biochars are more stable (Sun et al, 2014b). All feedstock ash content tends to remain in biochar, hence higher temperature biochars also have higher ash concentrations (Brownsort, 2009). Pyrolysis temperature can also affect the presence of char surface functional groups, which may in turn affect the char's ability for nutrient sequestration and soil amendment (Sun et al, 2014a). Biochars produced at high temperatures tend to have fewer oxygenated functional groups on the surface, i.e. fewer chemical receptor sites where compounds can be adsorbed on the biochar (Fuchs et al, 2014). Lower temperature biochars also tend to have lower pH values, lower SSA and higher CEC per unit surface area (Elad et al, 2011). Biochar properties affected by pyrolysis temperature are summarized in Figure 9.



**Figure 9.** Biochar properties depending on pyrolysis temperature  
*Summary of the effect of pyrolysis temperature on selected biochar properties.*

### 3.2 Physical and structural properties

Biochar has a skeletal structure composed of C and minerals of different pore size, consisting of (i) stable or fixed C, (ii) labile C and other volatiles, (iii) moisture, and (iv) ash components (Qambrani et al, 2017). Biochar is mainly composed of aromatic hydrocarbons with links of 6 C atoms without H or O (Chen et al, 2016; Yue et al, 2016). The aromatic structure is what makes biochar so resistant to microbial decomposition (Chen et al, 2016; Mimmo et al, 2014; Qambrani et al, 2017). Both pyrolysis temperature and feedstock type have a strong influence on the degree of aromaticity of biochar, and thereby also on biochar stability (Mimmo et al, 2014; Nanda et al, 2016). In general, more aromatic structures form at higher temperatures (Mimmo et al, 2014; Yuan et al, 2015).

Biochar has a complex porous structure and large SSA (Qambrani et al, 2017; Yue et al, 2016). Pore space determines SSA, which is very high for biochar; generally higher than sand and higher than or comparable to clay (Downie et al, 2009). The distribution of pore size (micro-, meso- and macropores) in biochar depends on pyrolysis conditions and feedstock (Nanda et al, 2016; Qambrani et al, 2017). Pore volume and porosity contributes to the WHC of biochar (Mimmo et al, 2014; Yue et al, 2016). Lastly, solid density increases with increasing temperature, and bulk density decreases (Downie et al, 2009). This is due to the significant loss of volatile and condensable compounds from the original feedstock, as well as the active pyrolysis of the cellulosic fragments and the condensation (shrinkage)

processes, resulting in an increased content of aromatic C clusters (Tsai et al, 2015). Biochars thus have higher solid density compared to their feedstocks (Downie et al, 2009; Qambrani et al, 2017).

### **3.3 Chemical properties**

The C content of biochar can vary between 65 and 90 % (Brown, 2009). Remaining elemental composition of biochar consists of C, hydrogen (H), N, sulfur (S) and oxygen (O) (Fuchs et al, 2014). Biochar also contains the inorganic components of the feedstock (ash). An increase in pyrolysis temperature causes decreased H and O content and increased C content, i.e. decreased H:C and O:C ratios (Brassard et al, 2016; Chen et al, 2016; Yue et al, 2016).

Ash-rich feedstock generates ash-rich biochar (Aller, 2016). Highest nutrient values are found in algae, manure/waste and cellulosic biomass, and the lowest in lignin-rich biomass. Pyrolysis temperature is another influential factor, as more nutrients are volatilized at higher temperatures. The available N-content in biochar is generally small. Macronutrients like calcium (Ca), magnesium (Mg), K and sodium (Na) can also be found in varying concentrations (ibid.). An increase in pyrolysis temperature will lead to higher ash content as alkali metals will accumulate in biochar (Chen et al, 2016). An enrichment of P, Mg, Ca, K and iron (Fe) has been observed with rising temperatures between 200°C and 700°C, though with varying percent retention, along with a decrease in plant-available N (Yuan et al, 2015). Almost all P from agricultural residue can be retained in biochar, though in a more stable form as it binds to Mg or Ca during thermal treatment (Dai et al, 2016). Increasing temperature also reduces bioavailability of the trace nutrients elements Mn, Fe, zinc (Zn) and copper (Cu) (Amonette & Joseph 2009). How much mineral content remains in biochar may depend of the properties of the mineral. Ca, for example, is mainly located in cell walls and will only be released during degradation at higher temperatures. P is associated with complex organic ions and only vaporizes at high temperatures. K ions on the other hand are very mobile and will vaporize at relatively low temperatures (ibid.). Due to the accumulation of ash and oxygenated functional group during pyrolysis, biochar is

generally alkaline, and pH increases with temperature (Chen et al, 2016; Mimmo et al, 2014; Yuan et al, 2015).

Surface chemistry of biochar is rich and varied (Amonette & Joseph 2009; Yue et al, 2016). Biochars can exhibit both hydrophilic, hydrophobic, acidic and basic properties, due to the varying nature of surface functional groups (Yue et al, 2016; Nanda et al, 2016). The relative contributions of these properties generally depend on feedstock and thermal degradation process (Yue et al, 2016). The surface charge of biochar can be both positive and negative but is mostly negative due to the dissociation of O-containing functional groups (Qambrani et al, 2017).

The adsorption capacity of biochar is high due to its surface characteristics, high porosity and high SSA (Yue et al, 2016). CEC corresponds to adsorption capacity. Because of its amphiphilic surface with both positive and negative surface charge, both anions and cations can be adsorbed (ibid.). At even higher temperatures, most O-containing compounds are driven off, which results instead in a neutral or slightly positive charge, and thus lower CEC (Fuchs et al, 2014). Therefore, biochar produced at lower temperature are generally better for soil CEC enhancement (Aller, 2016).

## 4. Uses of biochar

### 4.1 Carbon sequestration

Biochar can contribute for climate regulation by C sequestration through amendment to soil. The high C content and thermal stability of biochar makes it suitable for C sequestration (Gurwick et al, 2013; Nanda et al, 2016; Zhu et al, 2017). Application of biochar can contribute to climate regulation for as long as the char remains stable, and up to several thousand-year biochar stability has been estimated (Brassard et al, 2016). The biochar preserved in the Terra Preta soils is a historical indication of the long-term storage potential of biochar (Nanda et al, 2016).

A meta-analysis by Gurwick et al (2013) estimated biochar MRT to between 8 to almost 4000 years based on biochar decomposition rates.

Variations were attributed to a wide variety of ecosystems, soil conditions, feedstocks and pyrolysis conditions. In another meta-analysis by Wang et al (2016), MRT of labile soil C was estimated to about 108 days, and recalcitrant C to 556 years, which gives some indication of biochar MRT depending on percent labile and stabile C content. Generally, biochar in soils have longer MRT in temperate than in tropical climate, due to lower mineralization rates caused by lower temperature (He et al, 2016).

Biochar C mineralization varies depending on feedstock, pyrolysis temperature and climate and soil conditions (Ameloot et al, 2013; Crombie et al, 2015; Ding et al, 2017; Lian & Xing, 2017; Roberts et al, 2010; Wang et al, 2016b). Agricultural management practices can also influence biochar mineralization because mechanical disturbance increases decomposition rates (Ameloot et al, 2013). Increased pyrolysis temperature produces biochar with higher resistance to microbial decay, due to lower labile C-content and increased aromatic C content (Ameloot et al, 2013; Crombie et al, 2015; Ding et al, 2017; Gronwald et al, 2016; Lian & Xing, 2017; Wang et al, 2016b).

The greater the feedstock lignin content, the greater the aromatic C content and C:N ratio of resulting biochar and the smaller the mineralization rate (Ameloot et al, 2013; Bruun et al, 2011; Gronwald et al, 2016; Wang et al, 2016b). Hence, woody and herbaceous feedstock derived biochars experience slower mineralization rates relative to e.g. animal manure, sewage sludge, crop and grass derived biochars (de la Rosa et al, 2018; Gronwald et al, 2016; Wang et al, 2016b).

Soil mineral content, moisture, temperature and pH also affect stability (Lian & Xing, 2017; Wang et al, 2016b). Few studies have studied the effects of pH, but as pH has strong effects on soil microbial communities, it is logical to assume pH will affect biochar degradation (Lian & Xing, 2017). There is also a strong positive relationship between char oxidation and mean annual temperature (Wang et al, 2016b). Biochar mineralization is also sensitive to variation in moisture and disfavoured by saturated conditions that cause anaerobicity. Lastly, higher soil clay content results in slower decomposition (Wang et al, 2016b). Because OM binds to clay particles, clay-bound biochar may be less available to soil microorganisms, leading to increased resistance to degradation (Ameloot et al, 2013).

As of yet there is no consistent methodology to predict biochar stability based on its chemical properties (Aller, 2016). Spokas (2010) developed a method for assessing biochar stability based on O:C molar ratios, which is one of the most widely used and extensive methods developed so far (Aller, 2016). According to this theory, O:C molar ratio is negatively correlated with biochar stability (Spokas, 2010). VM content has also been suggested as a predictor for biochar stability, with lower VM content being more favourable (ibid.).

#### **4.2 Soil greenhouse gas emissions**

Biochar amendment can affect soil GHG emissions of N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub>.

The net CH<sub>4</sub> emission is the balance between methanogenesis and methanotrophy, i.e. between CH<sub>4</sub> production and oxidation (Hangs et al, 2016; Malghani et al, 2013) Methanotrophic activity, i.e. consumption of CH<sub>4</sub>, is favoured by the following factors: 1) improved soil structure (i.e. increased porosity and decreased bulk density), 2) alkaline pH, 3) low EC, 4) MC up to field capacity, and 5) high soil and biochar C:N ratio (Hangs et al, 2016). CH<sub>4</sub> production is favoured by anaerobic conditions, warm temperatures and presence of labile C (Brassard et al, 2016). Biochar affects soil conditions for example by improving aeration and/or WHC, i.e. creating conditions that favour CH<sub>4</sub> oxidation (Brassard et al, 2016).

Microbial nitrification and denitrification are the major sources of N<sub>2</sub>O emissions from soil (Brassard et al, 2016). Biochar application affects N<sub>2</sub>O emissions by affecting the fate and transformation of N in soils through activity of denitrifying bacteria. Primarily, biochar increases soil pH, which alters the N<sub>2</sub>O:N<sub>2</sub> ratio during denitrification (Ameloot et al, 2013; Hangs et al, 2016; Nguyen et al, 2017; Sun et al, 2014b). Other commonly suggested mechanisms are decreased N availability for microbes by sorption of mineral N to biochar surface (Ameloot et al, 2013; Felber et al, 2014; Hangs et al, 2016; Nelissen et al, 2014; Nguyen et al, 2017; Sun et al, 2014b), decreased substrate availability by sorption of labile C (Felber et al, 2014; Nguyen et al, 2017) and improved soil aeration by increased porosity (Ameloot et al, 2013; Hangs et al, 2016; Nguyen et al, 2017; Zheng et al, 2012).

Changes in soil CO<sub>2</sub> emissions following biochar addition is possibly linked to the labile C fraction of the biochar, which may either stimulate or repress soil respiration through changes in soil microbial abundance and community structure (Bamminger et al, 2014; Gomez et al, 2014; Gurwick et al, 2013; Lanza et al, 2016; Zhu et al, 2017). Biochar is considered to have the ability to positively or negatively prime native SOC, which might explain observed changes in soil respiration (Ramlow & Cotrufo, 2018). Priming is the stimulation of soil microbial community due to addition of various organic amendments (Sun et al, 2014b). Positive priming (increases in SOC derived CO<sub>2</sub>) has been explained by inputs of labile biochar C, or microbial protection from predators that stimulate mineralization. Negative priming (decreases in SOC derived CO<sub>2</sub>) might be explained by direct sorption of labile OM on or within biochar (Ramlow & Cotrufo, 2018). Aside from priming, increased CO<sub>2</sub> emissions may be due to mineralization of the biochar itself and/or abiotic release of biochar C (Ameloot et al, 2013). However, most studies cannot differentiate between biochar C and initial SOC due to method limitations. Biochar amendment might also affect the soil C cycle in additional ways. For example, if biochar could stimulate plant growth and increase photosynthetic C fixation, plant and root-derived soil C inputs may indirectly enhance the amount of CO<sub>2</sub> stored as SOC (Lorenz & Lal, 2014).

### **4.3 Soil amendment**

Application of biochar has gained particular interest as a method for agricultural soil improvement. The idea is for biochar to improve certain soil characteristics that improve soil fertility, as it shares many structural characteristics with OM and clay particles (Downie et al, 2009). Biochar has two main features making it appropriate for this use: 1) high stability against decay and 2) superior ability to retain essential plant nutrients (Nanda et al, 2016). Soil parameters that are primarily affected by biochar amendment are soil structure, WHC, pH, nutrient retention and bioavailability, toxicity and bioavailability of hazardous substances, soil thermodynamics and conditions for soil biota.

#### *4.3.1 Soil structure*

Higher porosity and SSA from biochar improves aeration and soil structure through aggregation (Nanda et al, 2016; Usowicz et al, 2016; Qambrani et al, 2017). Increased porosity occurs due to formation of macropores when biochar particles settle and by the internal porosity of the biochar itself (Usowicz et al, 2016). As the micropores allow diffusion of water and air, SBD is reduced (Chen et al, 2016). With passing time, sorption capacity of biochar will decrease as pores become clogged, partly by colonizing microorganisms and soil biota, which deactivates the biochar (Qambrani et al, 2017). By these mechanisms, biochar can also alter soil WHC (Brassard et al, 2016; Biederman & Harpole, 2013; Usowicz et al, 2016; Qambrani et al, 2017). Biochar can not only increase the water content of sandy soils but also cause less water to be held by clay soils (Downie et al, 2009).

#### *4.3.2 pH*

Due to the generally high ash content of biochar, it causes an increase in soil pH (Chen et al, 2016; Biederman & Harpole, 2013; Brassard et al, 2016; de la Rosa et al, 2018). The effect is most pronounced in acidic soils (Chen et al, 2016). However, the liming effect of biochar might be short lived due to weathering which lead to a decrease of basic sites on the biochar surface (de la Rosa et al, 2018). The magnitude of this decrease is determined by the intensity of the leaching and the acid-buffering capacity of the system (ibid.).

#### *4.3.3 Nutrient retention and bioavailability*

Biochar has similar properties to SOM and even has superior ability to retain plant nutrients compared to any other forms of SOM (Nanda et al, 2016). This is attributed to higher surface area, more negative surface charge and greater charge density than typical SOM (ibid.). Improved nutrient retention means higher availability of nutrients to plants and reduced leaching (Biederman & Harpole, 2013; Nanda et al, 2016; Li et al, 2016; Qambrani et al, 2017), which could indirectly reduce dependency on artificial fertilizers and improve the quality of runoff water. CEC is a measure of soil fertility (Nanda et al, 2016). The porous structure, high SSA of biochar and charged surface area means that it readily interacts with soil components, and hence the presence of biochar influences CEC and allows for retention of nutrients (Biederman & Harpole, 2013; Qambrani et al, 2017). Biochar is

not a fertilizer but can serve as a slow-releasing reservoir of nutrients (Brassard et al, 2016). The total N content of biochar is low (Aller, 2016). Hence, biomass N is not returned to the soil with biochar addition. This might be compared to e.g. anaerobic digestion of organic material to produce biogas, in which case the high nutrient digestate can be returned to the soil as fertilizer. Of course, this is at the expense of biochar production. On the other hand, nearly all biomass P is retained in biochar (Dai et al, 2016). Compared to fertilizer or agricultural residue, biochar P is less mobile, thanks to the sorption capacity of biochar. Therefore, biochar has been suggested as a strategy for recycling P to agricultural soils through reduced leaching and provision of a long-lasting P source to the soil (ibid.).

#### *4.3.4 Toxicity and bioavailability of hazardous substances*

Biochar adsorbs both organic and inorganic contaminants, heavy metals and pesticides (Brassard et al, 2016). Pollutant removal by biochar is mainly based on the presence of functional groups and charges on the biochar surface (Qambrani et al, 2017). Such groups can bind and thus remove e.g. Cu, lead (Pb) and aluminium (Al) (ibid.). Biochar also contains P which, as well as being a plant macronutrient, can immobilize heavy metals (Li et al, 2016). Furthermore, the biochar induced liming effect will reduce mobility of toxic elements such as Al and manganese (Mn) (Biederman & Harpole, 2013; Qambrani et al, 2017). Organic contaminants can also be removed by sorption or interaction with surface functional groups (Qambrani et al, 2017). The biochars produced at temperature high enough to be dominated by aromatic C-containing groups are efficient at adsorbing heavy metals and hazardous molecules such as pesticides and persistent organic pollutants (POPs) (Qambrani et al, 2017; Yue et al, 2016).

#### *4.3.5 Soil thermodynamics*

Though relatively little research exists on this subject, biochar has been suggested to alter thermodynamic properties of soil. This might be important, as thermodynamics play a large role in the soil energy balance and resulting temperature distribution (Usowicz et al, 2016). The dark colour of biochar suggests that albedo is affected (Gurwick et al, 2013; Usowicz et al, 2016). This may accelerate soil respiration and affect soil nutrient availability, ecosystem water dynamics, species composition, and growing

season length (Gurwick et al, 2013). It could also facilitate rapid germination, allowing more time for plant growth (Biederman & Harpole, 2013). Bulk density and soil water properties are considered to be the main factors influencing soil thermal properties (Uowicz et al, 2016).

#### *4.3.6 Conditions for soil biota*

The physicochemical properties of biochar induce changes that can affect soil microbes and biota, though specific mechanisms of biochar-microbe interactions are not well known (Chen et al, 2016; Zhu et al, 2017). The changes in soil structure provided by biochar, e.g. aeration, water content and pH, improves nutrient accessibility and facilitates movement of microbes (Lehmann et al, 2011; Zhu et al, 2017). pH may be the most important factor, as bacteria and fungi have different pH tolerance (Zhu et al, 2017). Generally, bacterial abundance is positively correlated with soil pH, and this is one way in which biochar can alter microbial community structure (Chen et al, 2016). Biochar also provides habitats for soil microorganisms and biota as these can colonise the porous and breakdown resistant biochar, which provides protection from predators like protozoa and micro-arthropods (Elad et al, 2011; Nanda et al, 2016; Qambrani et al, 2017; Yue et al, 2016; Zhu et al, 2017). Biochar with high ash content can supply nutrients to soil microbes, though often the elements exist in non-mineralizable forms (Nanda et al, 2016; Zhu et al, 2017). Observed effects on soil microorganisms vary. Most studies agree that overall microbial biomass increases in biochar amended soil and that microbial community composition is affected (Biederman & Harpole, 2013; Elad et al, 2011; Chen et al, 2016; Lehmann et al, 2011).

## Appendix 2: Calculated values

### Calculations of enthalpy of pyrolysis

Daugaard & Brown (2003) give the following values for enthalpy of pyrolysis at 500°C on a dry biomass basis:

- Woody biomass (oak): 1.46 MJ/kg
- Herbaceous biomass (average of oat hulls and corn stover): 1.07 MJ/kg

Van de Velden (2010) give the following values of specific heat capacity ( $c_p$ ) of biomass at 500°C:

- Wood: 1.38 kJ/(kg·K)
- Herbaceous biomass: 1.07 kJ/(kg·K)

The definition of enthalpy of pyrolysis ( $H$ ) in this report is the sum of sensible and reaction enthalpy. It is assumed that reaction enthalpy is independent of temperature, i.e. that the only change between pyrolysis at 500°C and 700°C is sensible enthalpy. The change in enthalpy of pyrolysis at different temperatures can thus be calculated using equation 1.

$$Q = m \cdot c_p \cdot (T_2 - T_1) \quad (1)$$

#### *Woody biomass*

- $Q = 1 \text{ kg} \cdot 1.38 \text{ kJ}/(\text{kg} \cdot \text{K}) \cdot 700 \text{ }^\circ\text{C} - 500 \text{ }^\circ\text{C} = 276 \text{ kJ} = 0.276 \text{ MJ/kg}$
- $H = 1.46 \text{ MJ/kg} + 0.276 \text{ MJ/kg} = 1.74 \text{ MJ/kg}$

#### *Herbaceous biomass*

- $Q = 1 \text{ kg} \cdot 1.07 \text{ kJ}/(\text{kg} \cdot \text{K}) \cdot 700 \text{ }^\circ\text{C} - 500 \text{ }^\circ\text{C} = 214 \text{ kJ} = 0.214 \text{ MJ}$
- $H = 1.07 \text{ MJ/kg} + 0.214 \text{ MJ/kg} = 1.28 \text{ MJ/kg}$

### **Calculations of syngas heat of combustion**

The energy content of bio-oil is 40% and syngas 15% of that of petroleum fuels (Miller-Robbie et al, 2015). Thus, if bio-oil heat of combustion equals 18 MJ/kg (woody biomass) and 16 MJ/kg (herbaceous biomass) (Jahirul et al, 2012) this means that syngas heat of combustion is 7 MJ/kg (woody biomass) and 6 MJ/kg (herbaceous biomass). Due to lack of data no distinction is made between the two temperatures (500°C and 700°C).



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